Engine Intake Aerothermal Design: Subsonic to High Speed Applications

Intake Noise Generation; Source Mechanisms

Intake Noise Issues; Measurement, Modeling & Prediction, and Mitigation

Ed Envia

NASA Glenn Research Center

VKI Lecture Series

Von Karman Institute

November 14 – 16, 2011

National Aeronautics and Space Administration

Intake Noise Generation

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ENGINE INTAKE AEROTHERMAL DESIGN: SUBSONIC TO HIGH SPEED APPLICATIONS

Outline

- Introduction to Engine Intake (Inlet) Noise
  - A brief discussion of the impact of aircraft engine inlet noise on the environment and how its effect is quantified.
- Generation Mechanisms
  - An overview of various source mechanisms of engine inlet noise and their relative importance over the operational regime of the engine.
- Summary

Useful Reference
Aircraft Noise by Michael J. T. Smith, Cambridge Aerospace Series 1989.

Introduction

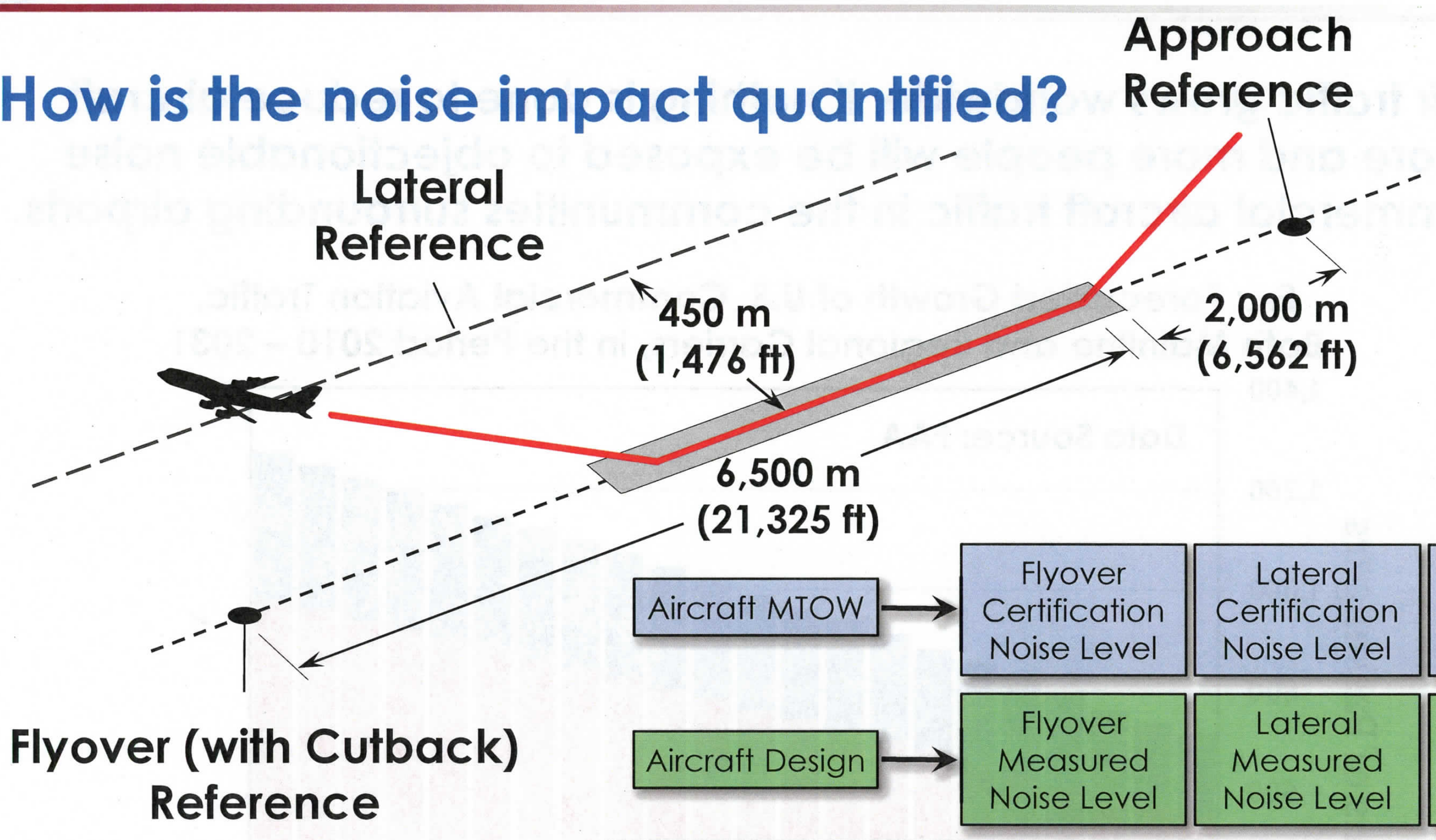
Environmental Impact of Aviation

Aircraft noise and emissions are regulated by international agreements.

Introduction

Community Noise Metric

How is the noise impact quantified?



Aircraft MTOW →	Flyover Certification Noise Level	Lateral Certification Noise Level	Approach Certification Noise Level	−
Aircraft Design →	Flyover Measured Noise Level	Lateral Measured Noise Level	Approach Measured Noise Level	
Noise Margin →	Flyover Noise Margin	Lateral Noise Margin	Approach Noise Margin	=

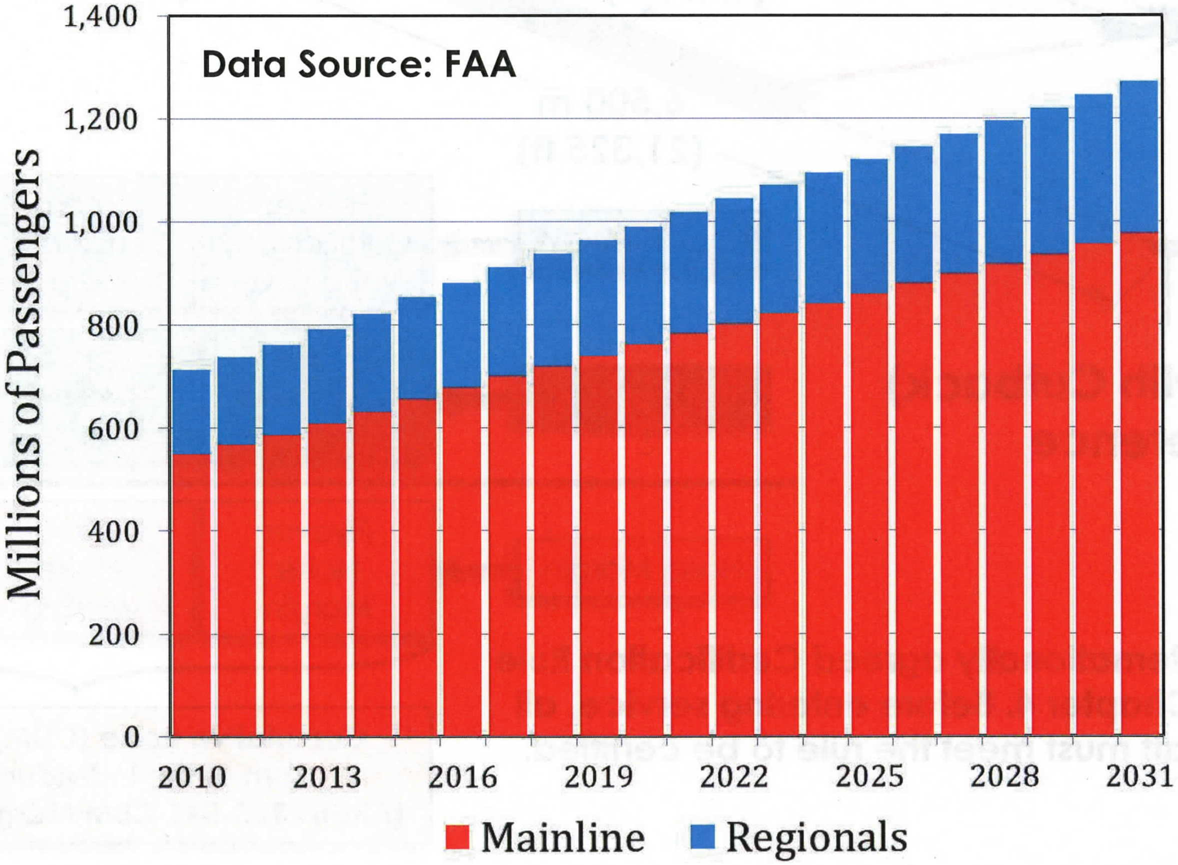
Cumulative noise (CUM) margin is the sum of the individual margins. (Airbus 380-842 CUM Margin = 16.4 EPNdB)

Current internationally agreed Certification Rule is called Chapter 4. Before entering service, all new aircraft must meet the rule to be certified.

Motivation for Noise Reduction Research

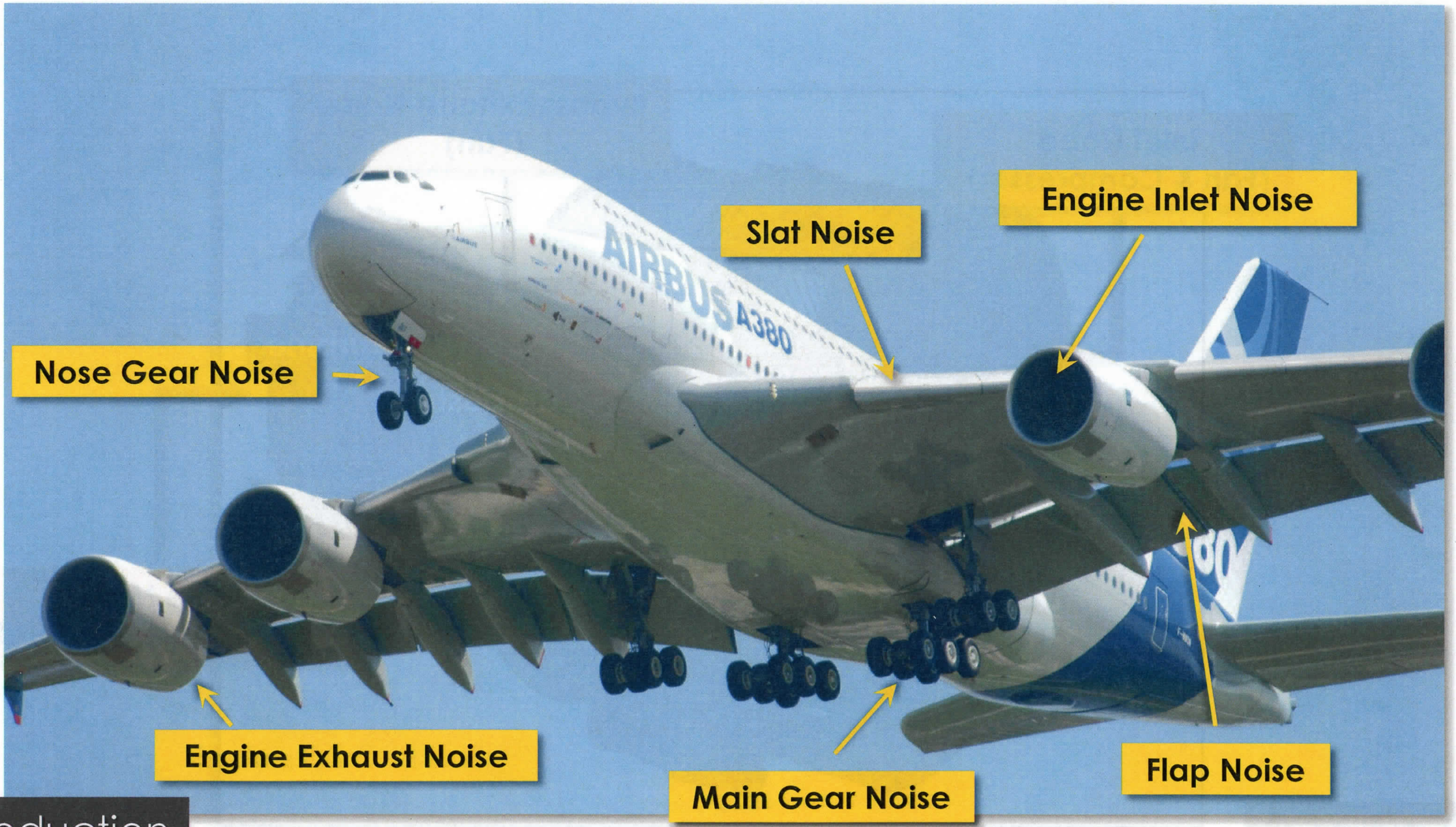
As the air traffic grows worldwide, if nothing is done to reduce aircraft noise, more and more people will be exposed to objectionable noise from commercial aircraft traffic in the communities surrounding airports.

Ex.: Forecasted Growth of U.S. Commercial Aviation Traffic, Both Mainline and Regional Carriers, in the Period 2010 – 2031



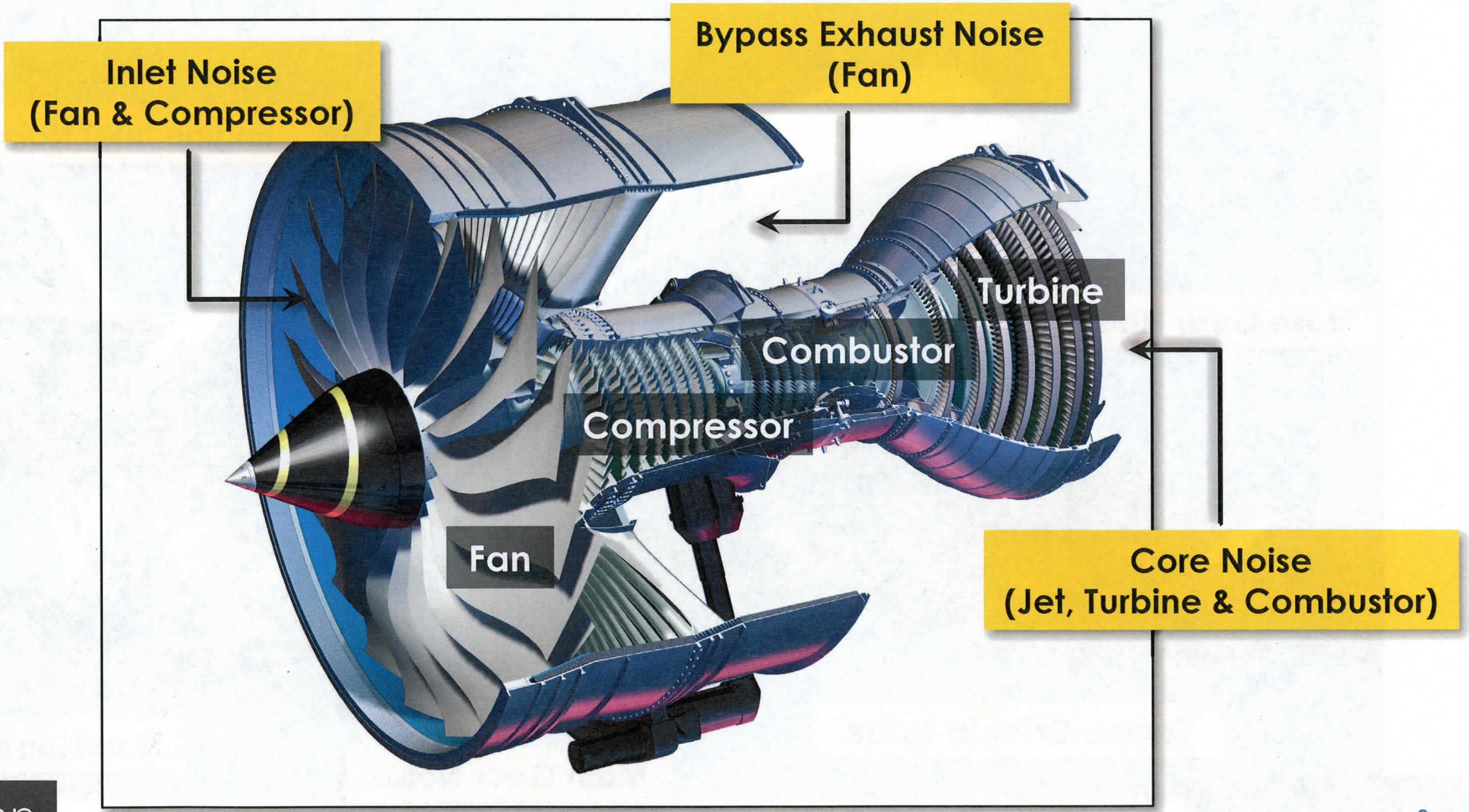
Sources of Aircraft Noise

Aircraft noise is a complex amalgam of sources, interactions, transmission, and propagation.



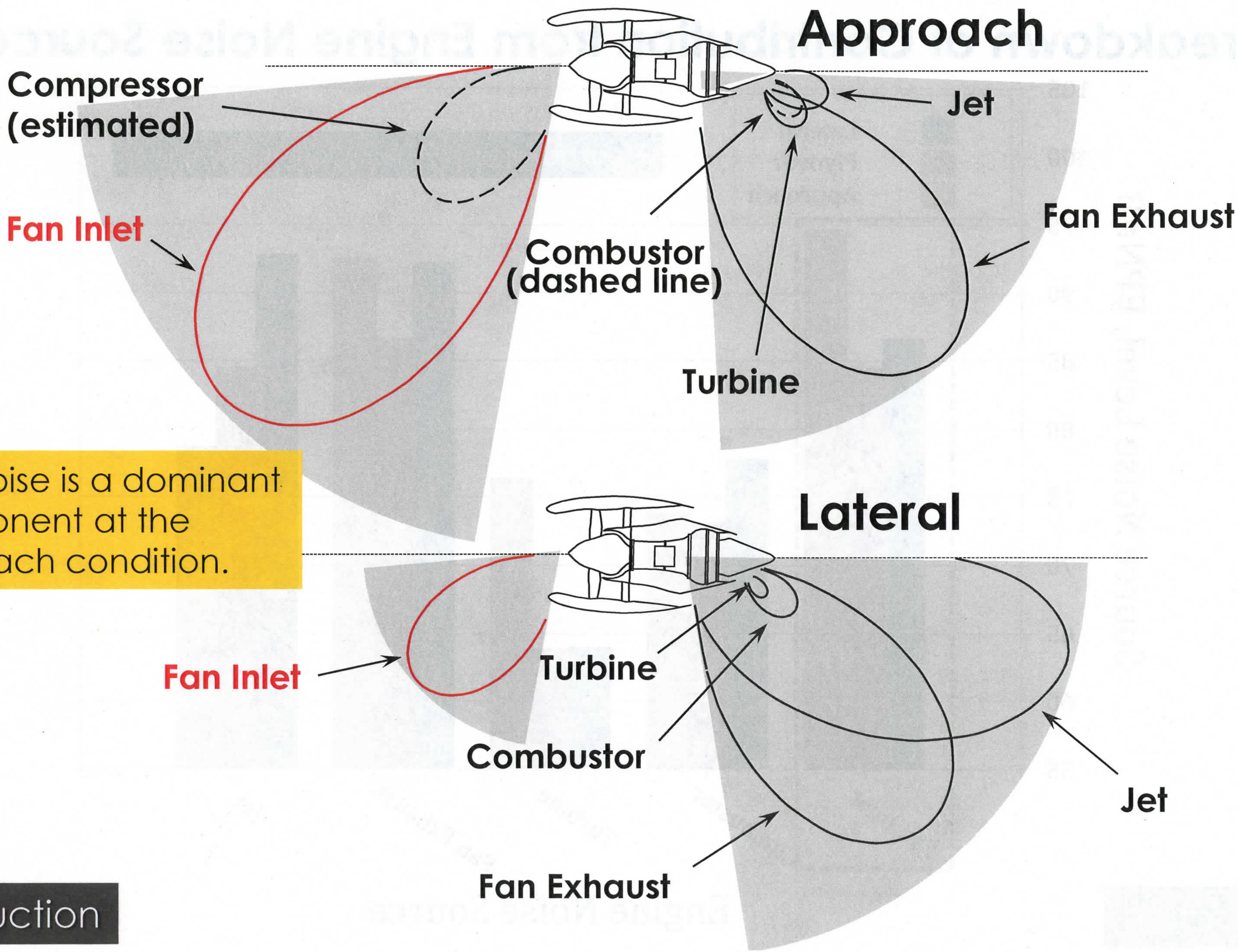
Engine Noise Sources

Engine noise is a major contributor to the total aircraft noise output.



Introduction

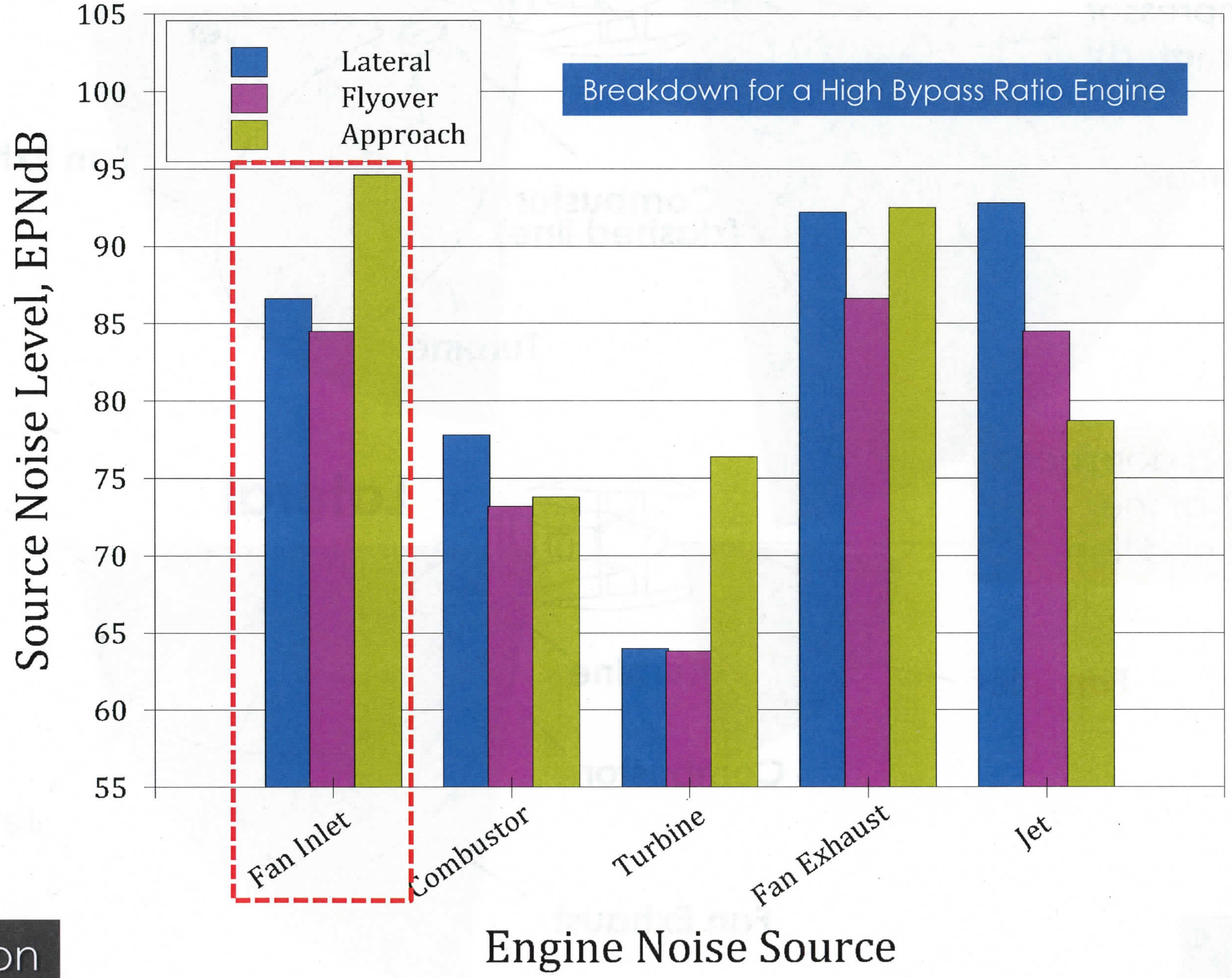
Characteristics of Engine Noise Sources



Inlet noise is a dominant component at the approach condition.

Engine Noise Source Levels

Breakdown of Contribution from Engine Noise Sources



Introduction

Generation

Inlet Noise Mechanisms

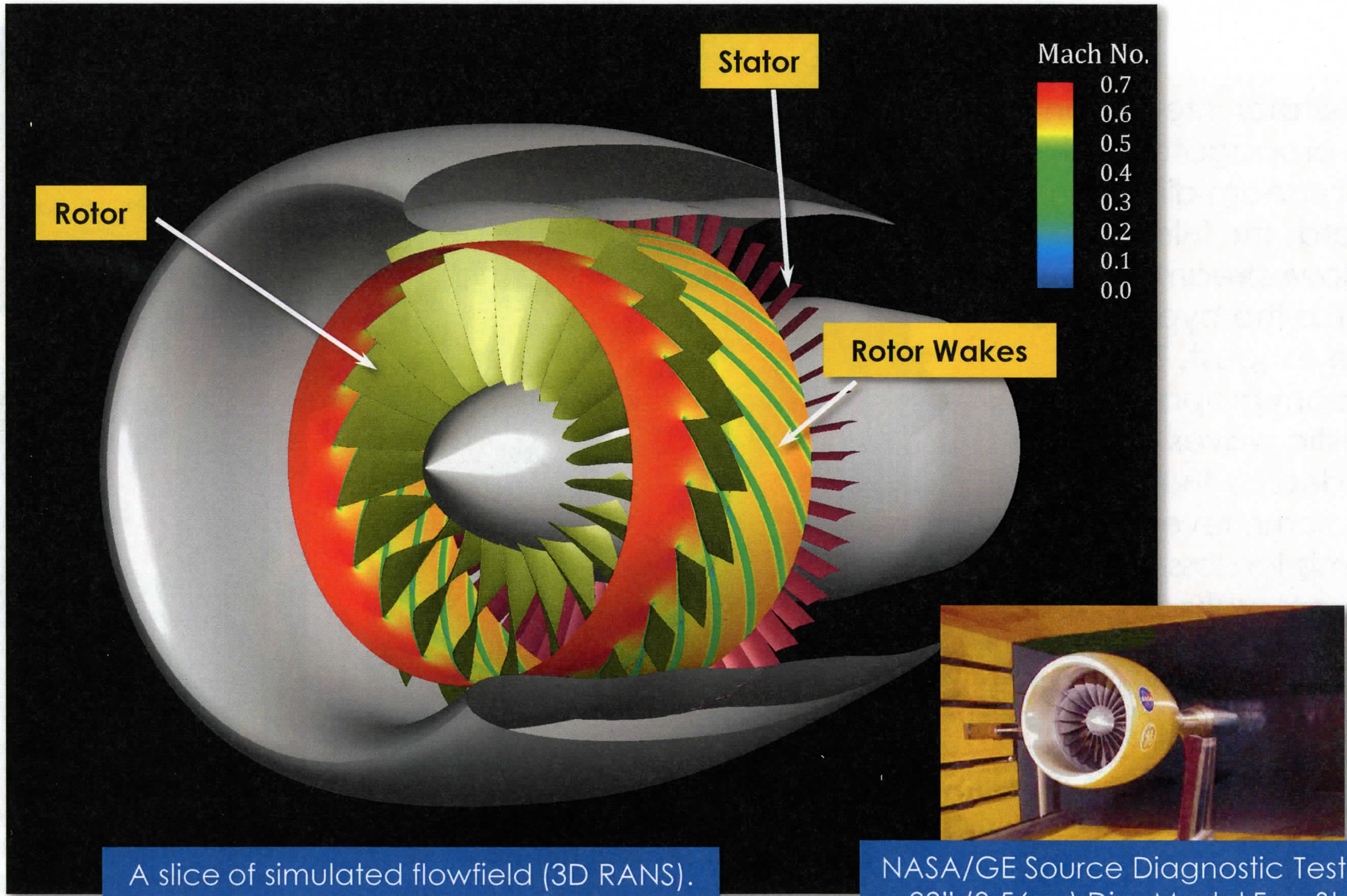
- As alluded to before, there are several sources (mechanisms) of noise generation that contribute to the inlet noise.

- These can be organized into two main categories; those generated by the fan rotor itself, and those produced by the interaction of rotor flowfield with stator guide vanes. Noise associated with the compressor, though typically small in comparison, can be included in the same categories.

- Three principal sources of inlet noise are rotor-stator interaction noise, rotor self-noise, and multiple pure tones noise.

Rotor-Stator Interaction Noise

A main source of noise for both inlet and exhaust is the fan noise associated with the interaction of rotor wakes with stator vanes.



A slice of simulated flowfield (3D RANS). Mach No. contours are shown.

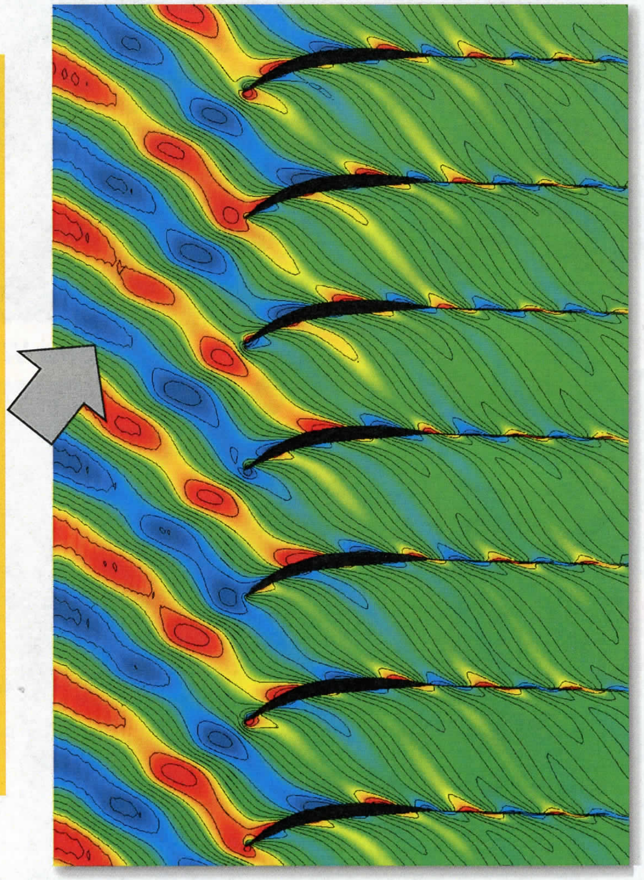
NASA/GE Source Diagnostic Test (SDT) 22" (0.56 m) Dia. Model Fan Stage

Generation

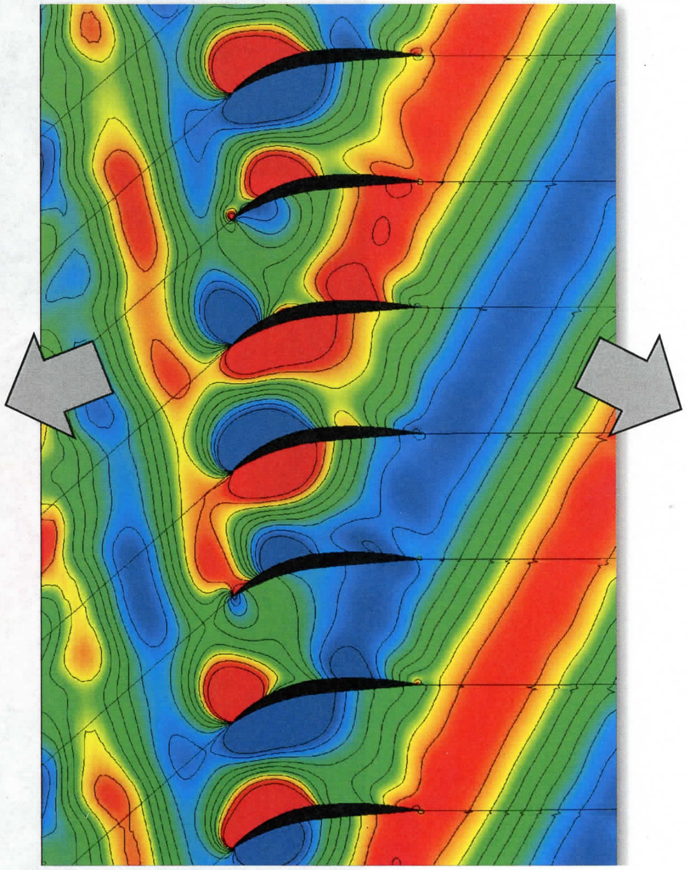
Rotor-Stator Interaction Noise (Cont'd)

Rotor wakes convect downstream and impinge on the stator vanes generating both tonal and broadband noise.

Rotor-Stator interaction noise propagates both in the upstream direction (towards the inlet) and in the downstream direction towards the bypass duct nozzle exhaust. The upstream propagating acoustic waves could be impeded by the rotor and suffer some level of transmission loss. Simulated coherent wake and tonal acoustic perturbation fields are shown (Linearized Euler calculations).



Rotor wake. Second harmonic of blade passing frequency is shown. A segment of the annulus depicted.



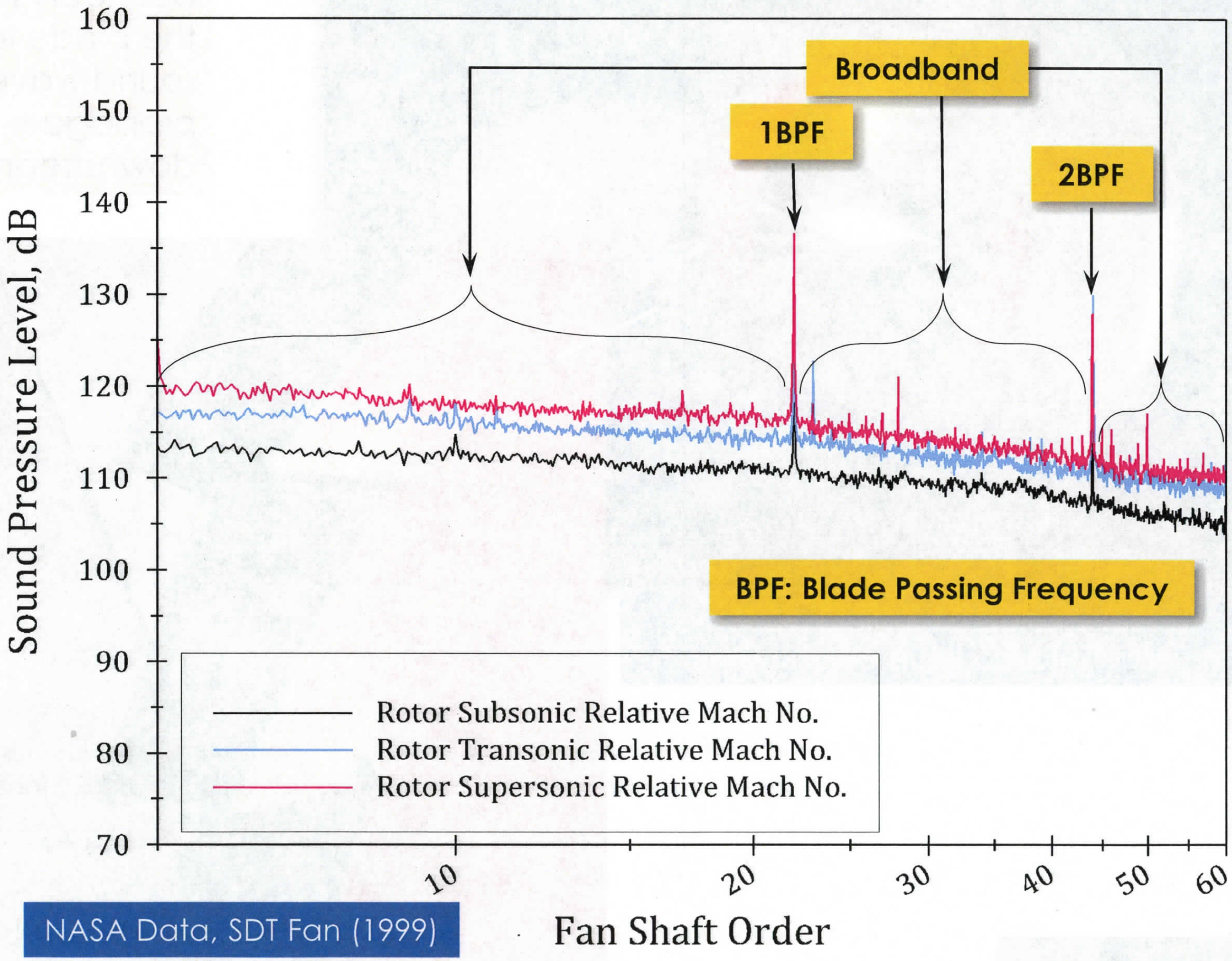
Acoustic waves generated by the wake impingement on the stator. Second harmonic of blade passing frequency is shown. This is a Linearized Euler simulation.

Generation

Rotor-Stator Interaction Noise (Cont'd)

Duct Wall Pressure Spectra Measured Between Rotor and Stator

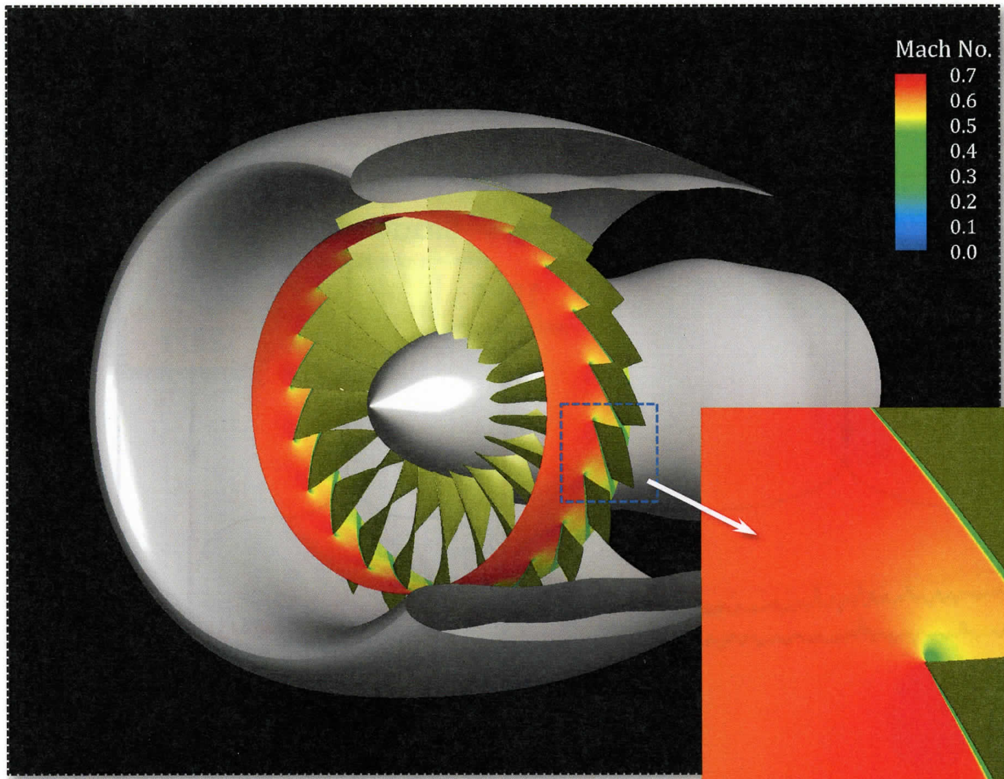
Rotor-stator interaction noise is comprised of both tonal and broadband components. Tonal noise is caused by the coherent part of the rotor wakes and broadband noise is caused by the turbulence downstream of the fan (both within and outside) of the wakes.



NASA Data, SDT Fan (1999)

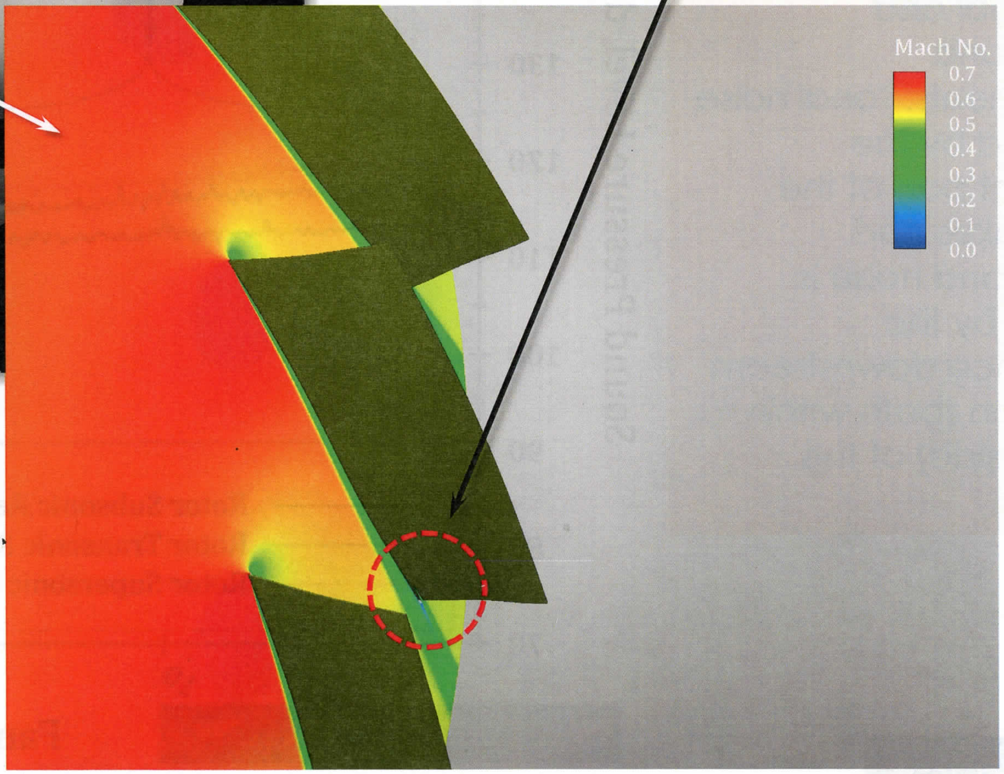
Generation

Rotor Self-Noise



A slice of simulated flowfield (3D RANS).
Mach No. contours are shown.

Turbulence energy in the blade boundary layer is scattered at the blade trailing edge into sound waves which can propagate both upstream and downstream.

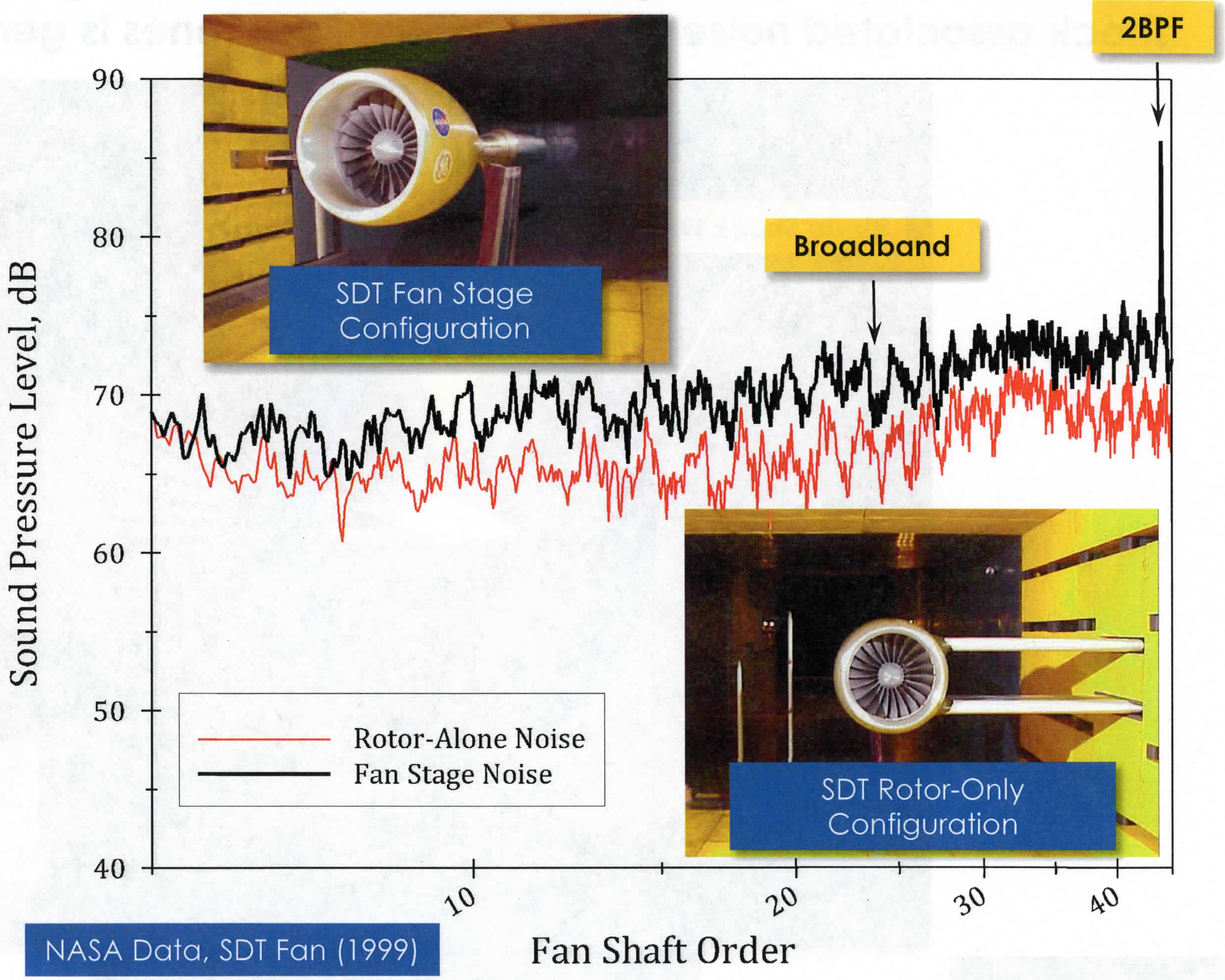


Generation

Rotor Self-Noise (Cont'd)

Measured Noise Level 4 Fan Diameters Away at 60° from Inlet Axis

Comparison of measured rotor-alone noise and stage noise shows that rotor self-noise is a significant contributor to the overall noise signature of the fan stage. Stage noise is comprised of both rotor-alone noise and rotor-stator interaction noise. Note that while rotor-stator noise exhibits both tonal and broadband content, rotor self-noise is strictly broadband.

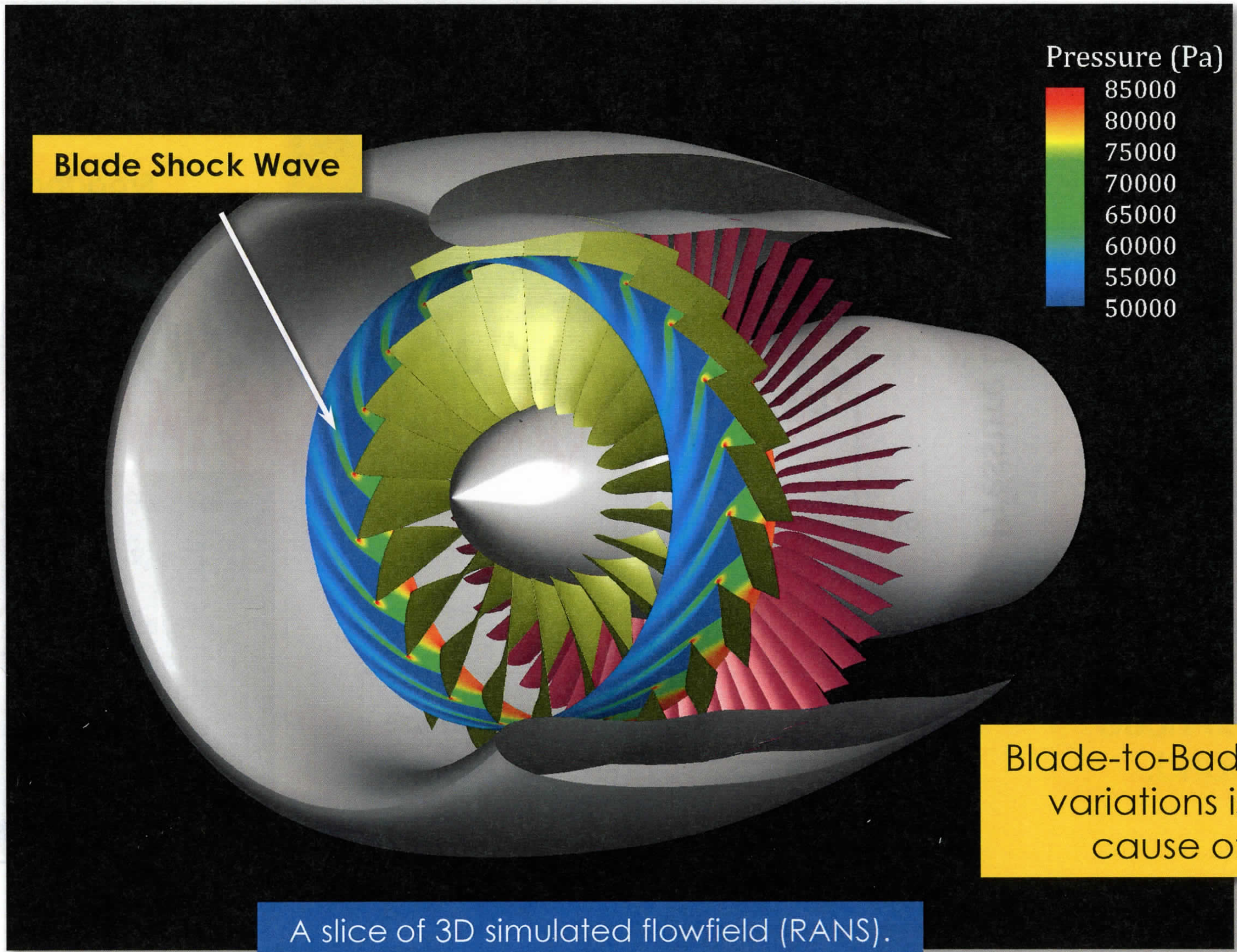


NASA Data, SDT Fan (1999)

Generation

Multiple Pure Tones

When the rotor relative Mach Number is equal to or greater than unity, shock associated noise called Multiple Pure Tones is generated in the inlet.



Blade-to-Bade stagger angle variations is the principal cause of MPT noise.

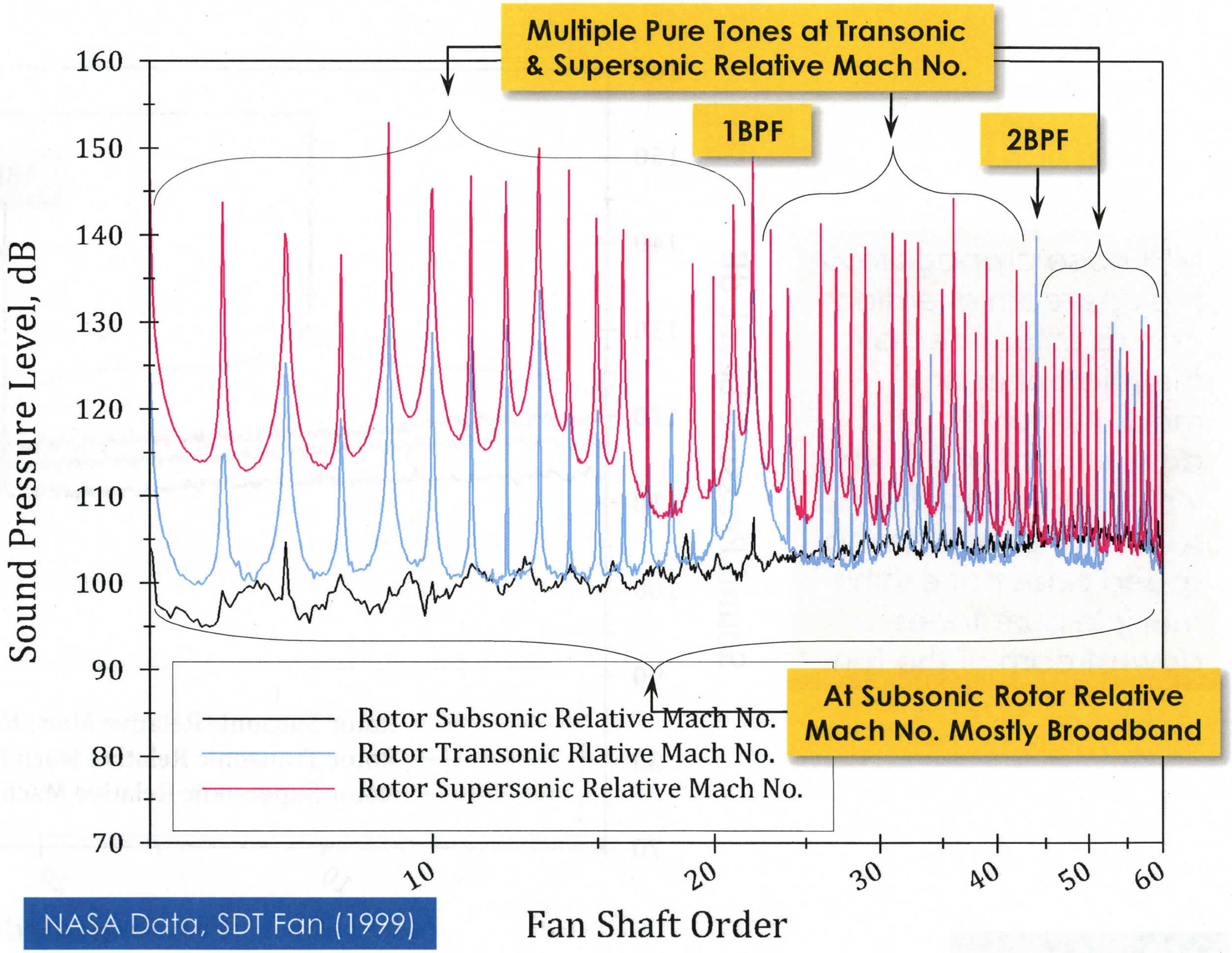
A slice of 3D simulated flowfield (RANS). Static pressure contours are shown.

Generation

Multiple Pure Tones (Cont'd)

Duct Wall Pressure Spectra Measured upstream of the Fan

As the fan tip speed increases, the character of inlet noise spectrum changes from one with significant broadband component and very few blade passing frequency harmonic tones to a spectrum primarily dominated by numerous fan shaft order tones (MPT noise) whose levels are significantly above the broadband.



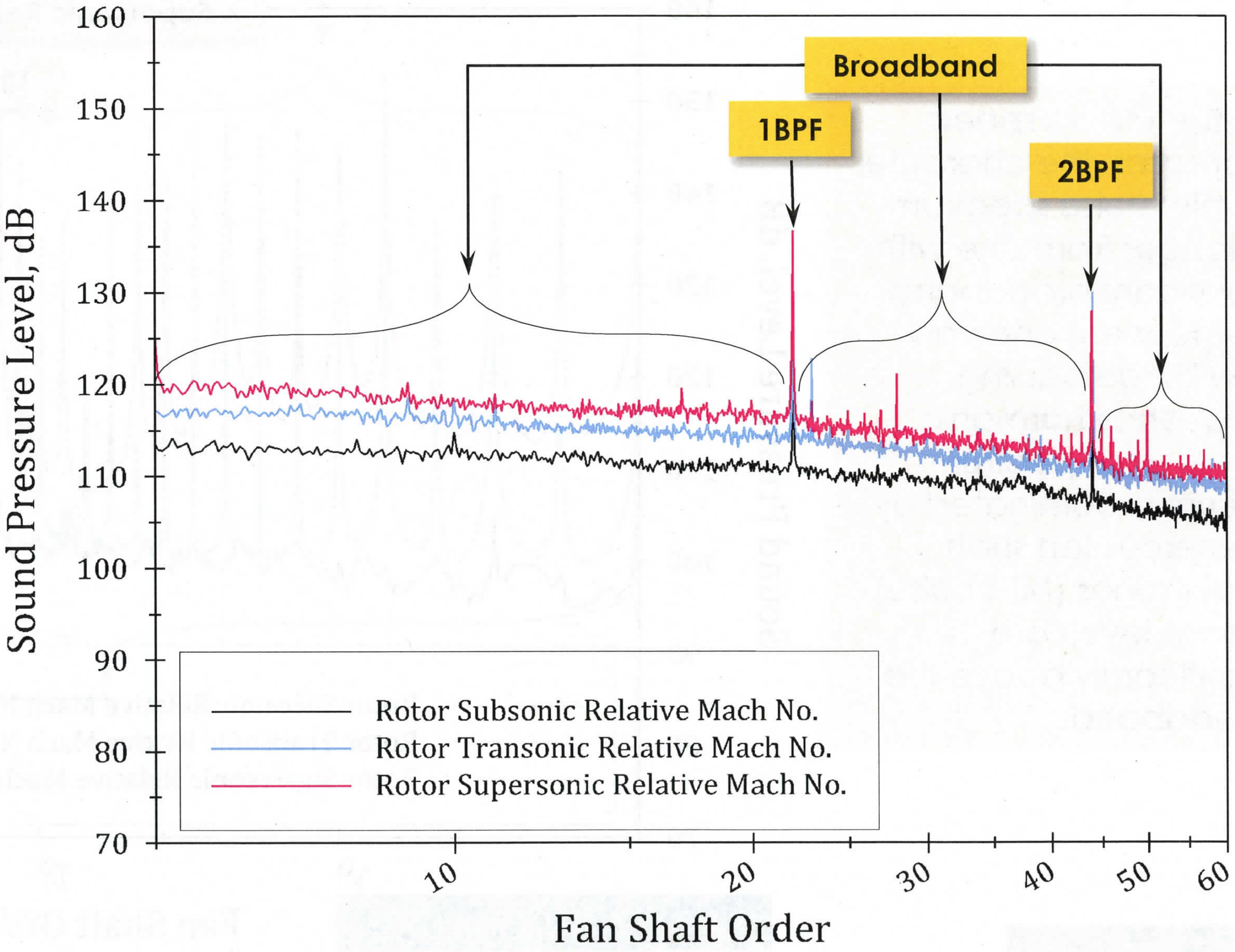
NASA Data, SDT Fan (1999)

Generation

Multiple Pure Tones (Cont'd)

Duct Wall Pressure Spectra Measured Between Rotor and Stator

MPT noise propagates in the upstream direction only as evidenced by the microphone measurements downstream of the fan which show that the spectrum at any fan tip speed does not exhibit multiple pure tones downstream of the fan.

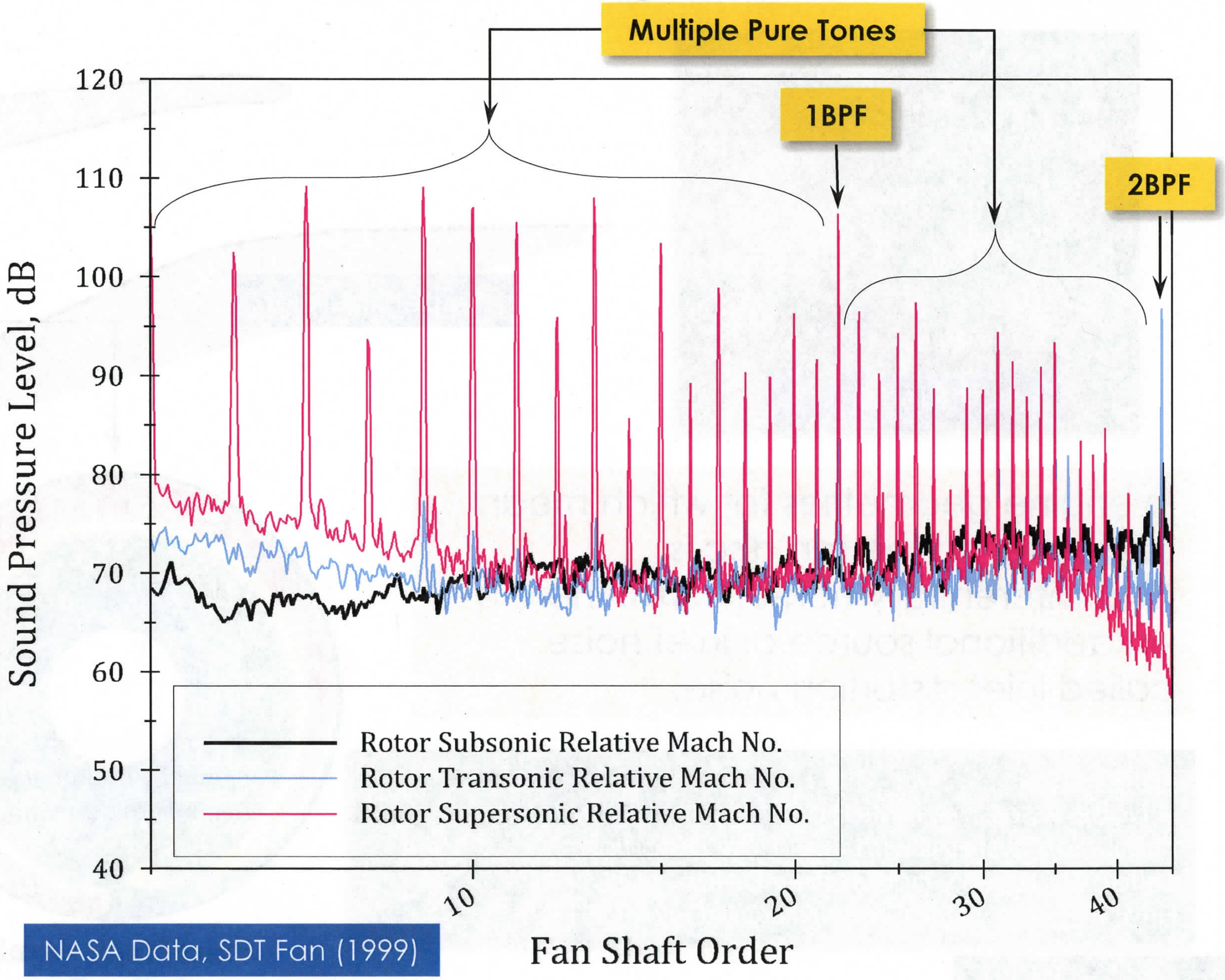


Generation

Multiple Pure Tones (Cont'd)

Measured Noise Level 4 Fan Diameters Away at 60° from Inlet Axis

Noise measurements outside the inlet and away from the nacelle show that MPT noise does indeed propagate outside of the inlet too and is far more significant than broadband noise at transonic and supersonic fan tip speed conditions.

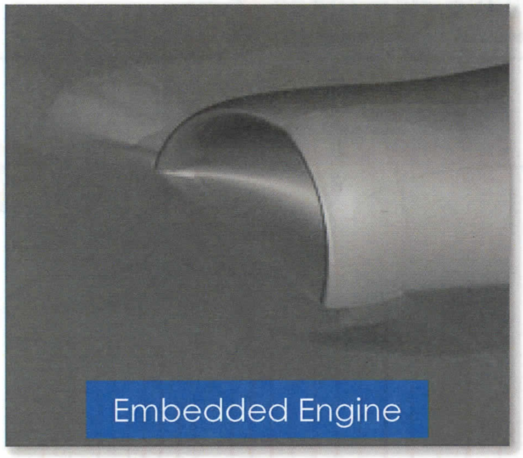


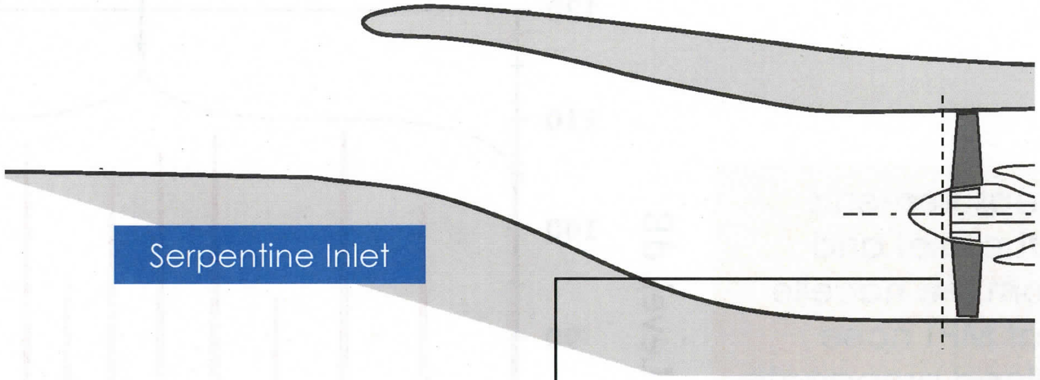
NASA Data, SDT Fan (1999)

Generation

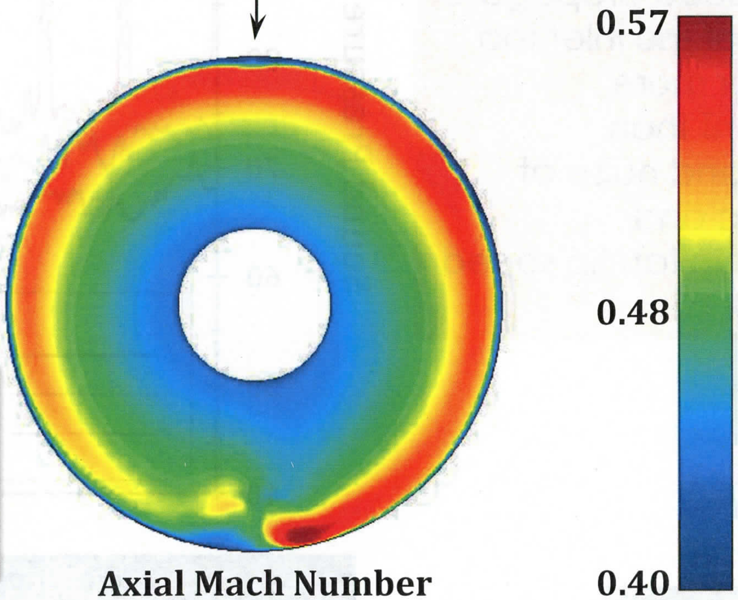
Inlet Distortion Noise

Additional Noise Source for Short Inlets and Highly Integrated Inlets





In engine geometries for which mean flow entering the fan disc is circumferentially non-uniform, there is an additional source of inlet noise called inlet distortion noise.



Axial Mach Number At Fan Face

Reference
A Noise Assessment Methodology for Highly-Integrated Propulsion Systems with Inlet Flow Distortion
Zoltan Spakovsky and Jeffrey Defoe, MIT
Final Report, NASA Grant NNX07AD42A (2011)

Summary

- Inlet noise is a significant contributor to engine noise at the approach condition.

- Principal sources of inlet noise are rotor-stator interaction noise, rotor self-noise, and multiple pure tones noise. The later source only occurs at rotor supersonic relative Mach numbers.

- For highly integrated inlets (e.g., embedded engines) or short inlets, inlet distortion noise is an additional source.

Questions?

National Aeronautics and Space Administration

Intake Noise Issues

Measurement, Modeling & Prediction, and Mitigation

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Outline

- Measurement Techniques
  - A discussion of the principal methods for measuring and characterizing inlet noise.

- Modeling & Prediction
  - An review of source and propagation modeling and prediction methodologies currently being used to model and predict inlet noise.

- Noise Mitigation
  - A summary of common techniques used for reducing inlet noise.

- Summary

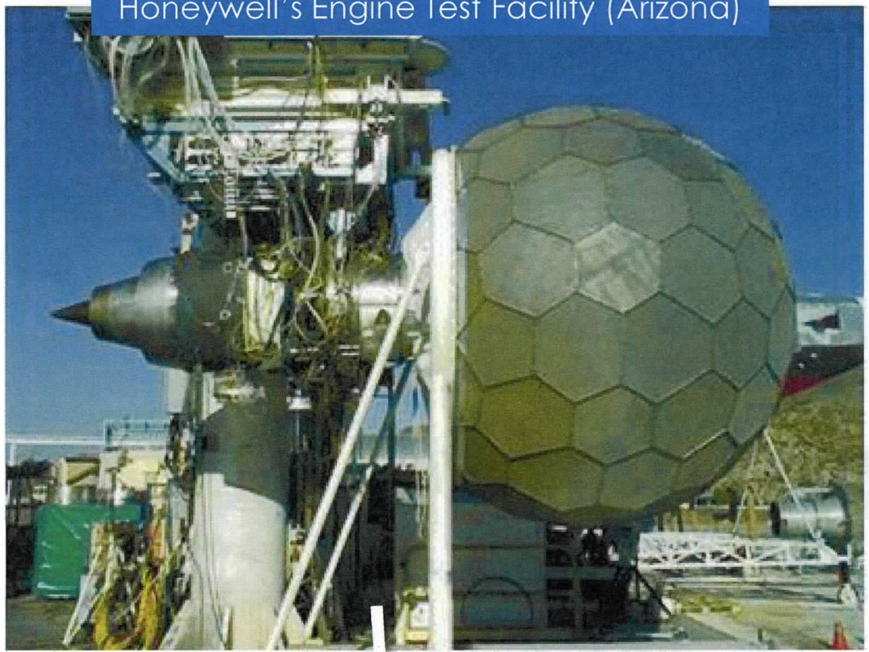
Useful Reference

Aeroacoustics by Marvin E. Goldstein, McGraw-Hill, Inc., 1976.

Measurement

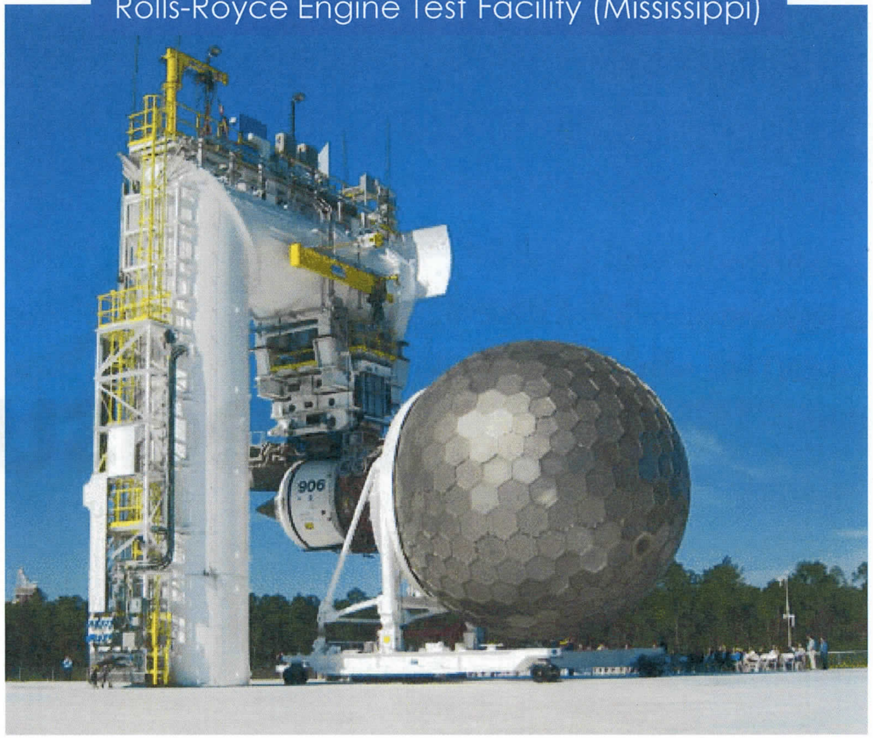
Source Noise Measurement

Honeywell's Engine Test Facility (Arizona)



Ground Microphone Arc

Rolls-Royce Engine Test Facility (Mississippi)



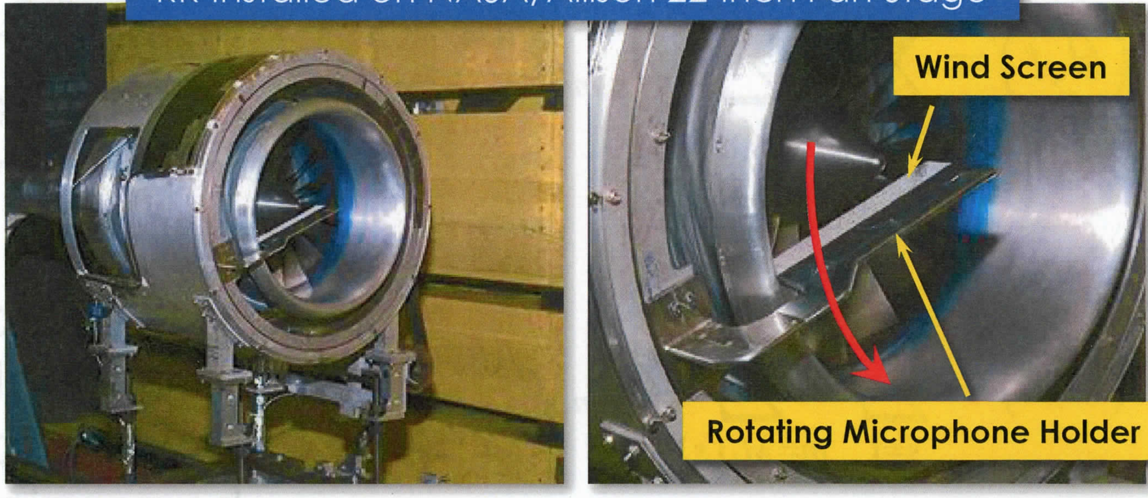
Engine inlet noise is often extracted from measurements of the overall engine noise using a variety of source separation techniques. This is because it is often difficult to directly measure the inlet noise contribution in an engine.

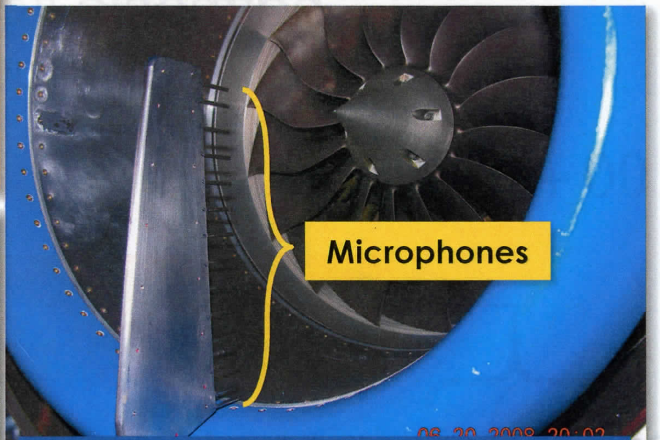
Diagnostics: Rotating Rake (RR)

The rotating rake system is designed to measure the modal content of coherent (i.e., tonal) fan noise inside the nacelle. The microphone rake is rotated at a fraction of the fan rotational speed. The system can be used both in the fan inlet and exhaust and has been successfully deployed in the wind tunnel as well as in full-scale engine tests.

Reference
The Rotating Rake Fan Mode Measurement System
Presented at 146th Meeting of Acoustical Society of America
Daniel Sutliff (2003)

RR Installed on NASA/Allison 22-inch Fan Stage





RR Installed on Williams International FJ44 Engine

RR Installed on Honeywell TFE731-60 Engine

Measurement

Diagnostics: Rotating Rake (Cont'd)

$$p'(\theta,t)=\sum_{s=1}^{\infty}\sum_{m=M_1(s)}^{m=M_2(s)} A_{s,m}\, e^{i(m\theta - sB\Omega t)}$$

In a fixed frame, fan modes corresponding to the harmonic order s all have the same frequency $sB\Omega$

$$p'(\theta,t)=\sum_{s=1}^{\infty}\sum_{m=M_1(s)}^{m=M_2(s)} A_{s,m}\, e^{i(m\omega - sB\Omega)t}$$

In the rotating rake frame, with rotational speed ω, $\theta=\omega t$ fan modes corresponding to the harmonic frequency s each have a unique frequency $sB\Omega - m\omega$

$$\omega=\frac{\Omega}{N},\quad N \text{ Typically } 100+$$

Each mode appears in a unique Doppler shifted frequency in the rake frame

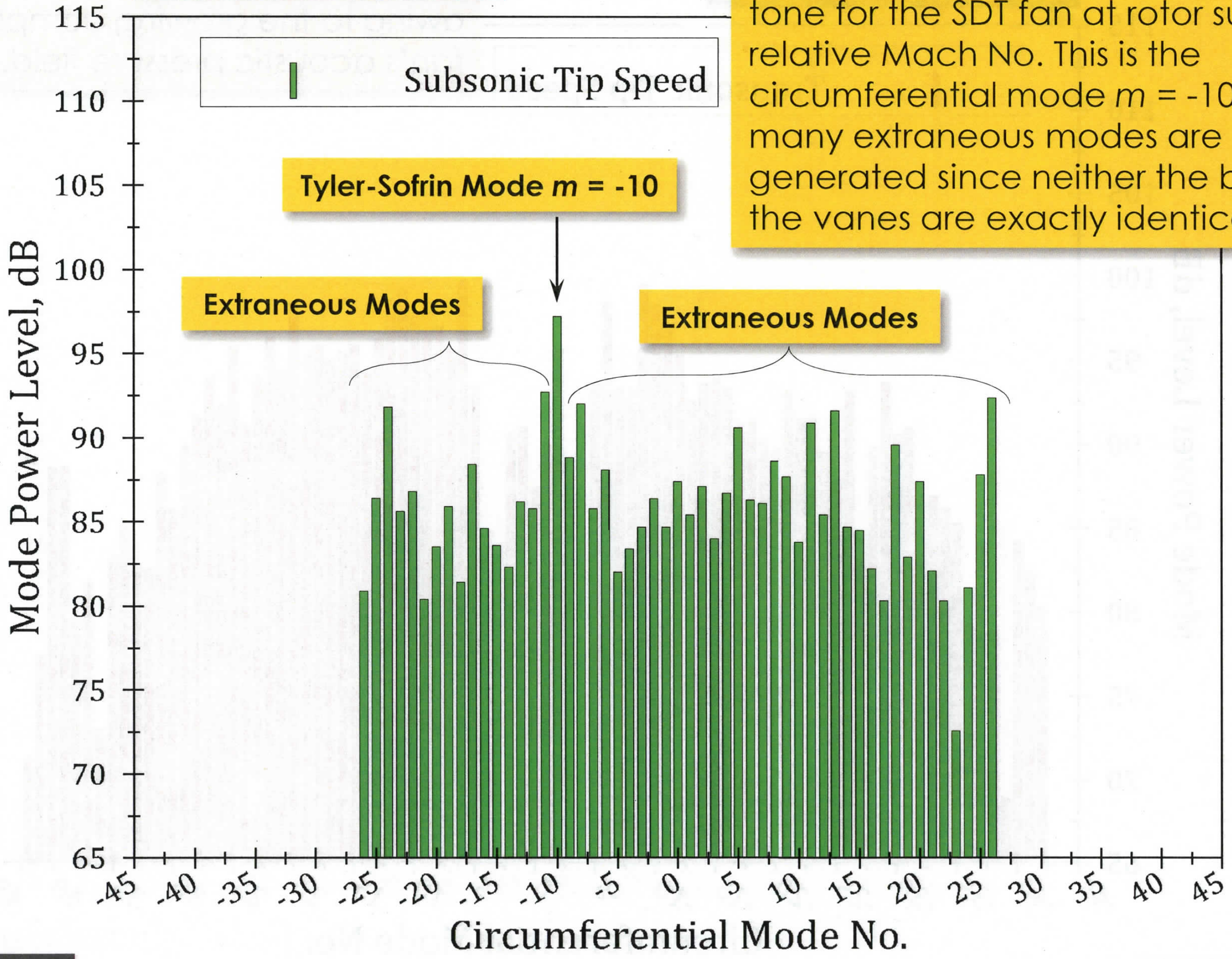
$$\text{Mode Frequency}=\left(sB-\overbrace{\frac{m}{N}}\right)\Omega$$

Mode Frequency in Rotating Rake Frame

Measurement

Diagnostics: Rotating Rake (Cont'd)

NASA Data – 2BPF Tone
SDT Fan (2000)



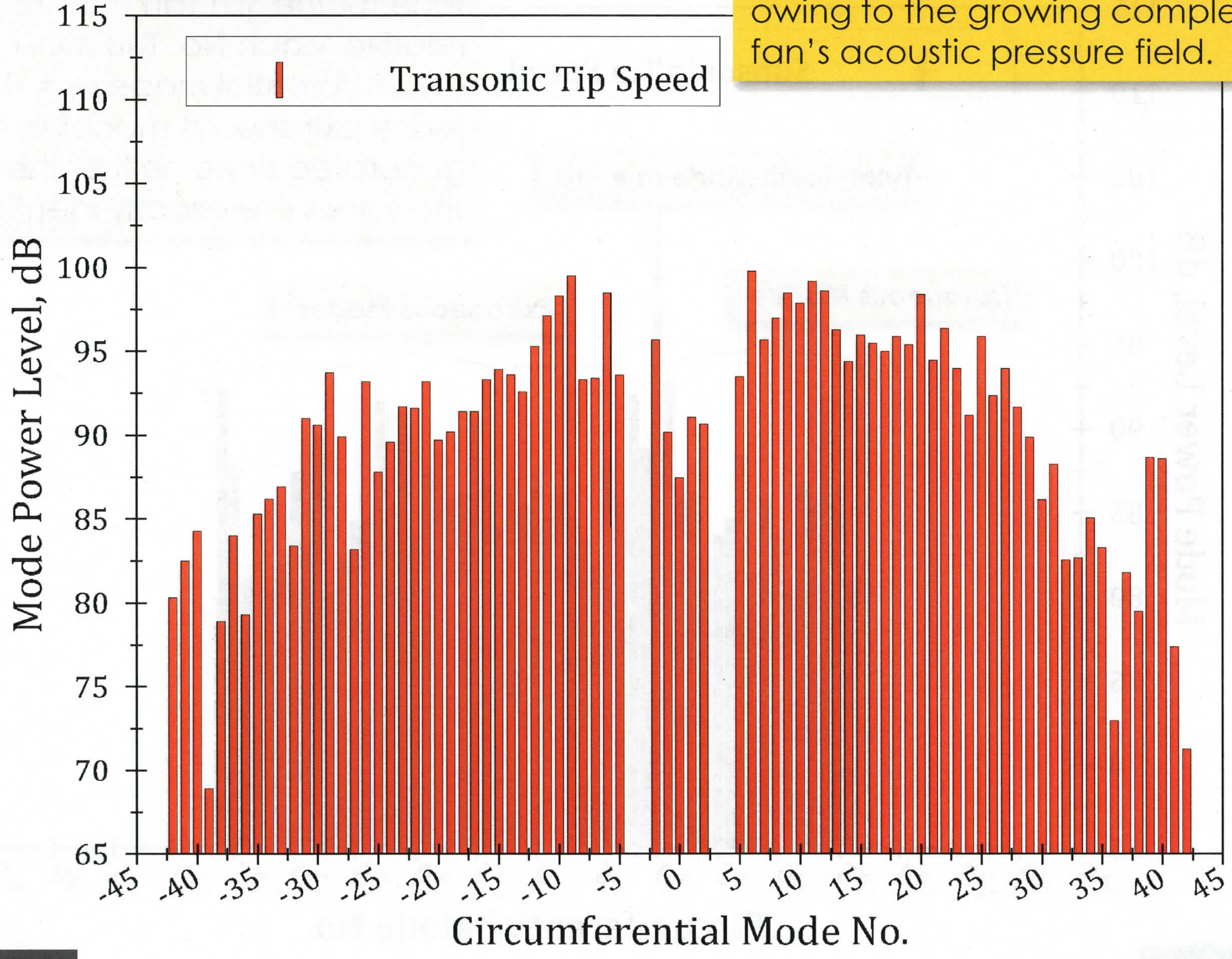
The Tyler-Sofrin theory predicts a single interaction mode generated at 2BPF tone for the SDT fan at rotor subsonic relative Mach No. This is the circumferential mode m = -10. In reality, many extraneous modes are also generated since neither the blades nor the vanes are exactly identical.

Measurement

Diagnostics: Rotating Rake (Cont'd)

NASA Data – 2BPF Tone
SDT Fan (2000)

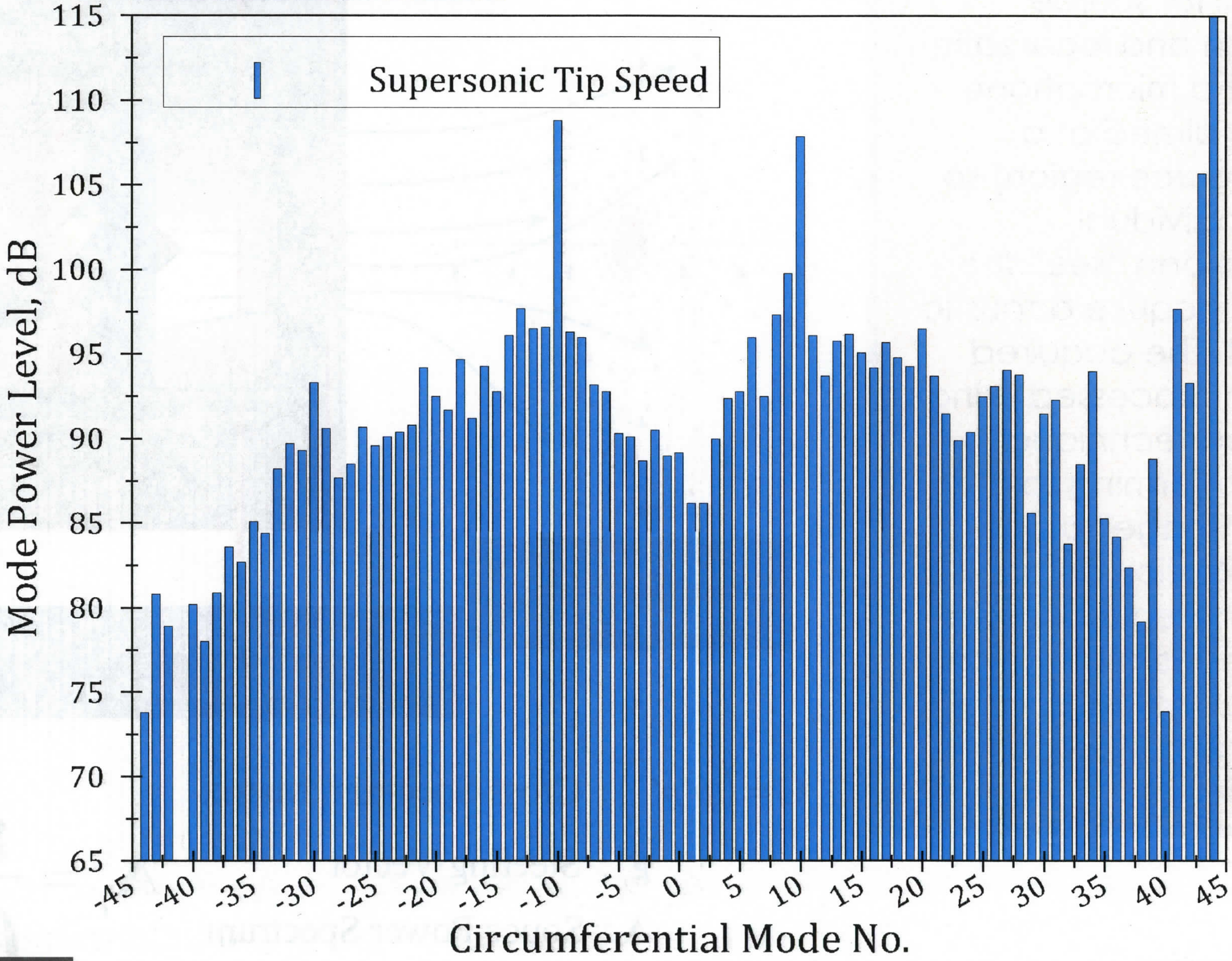
As the tip relative Mach No. increases, the number of modes increases too owing to the growing complexity of the fan's acoustic pressure field.



Measurement

Diagnostics: Rotating Rake (Cont'd)

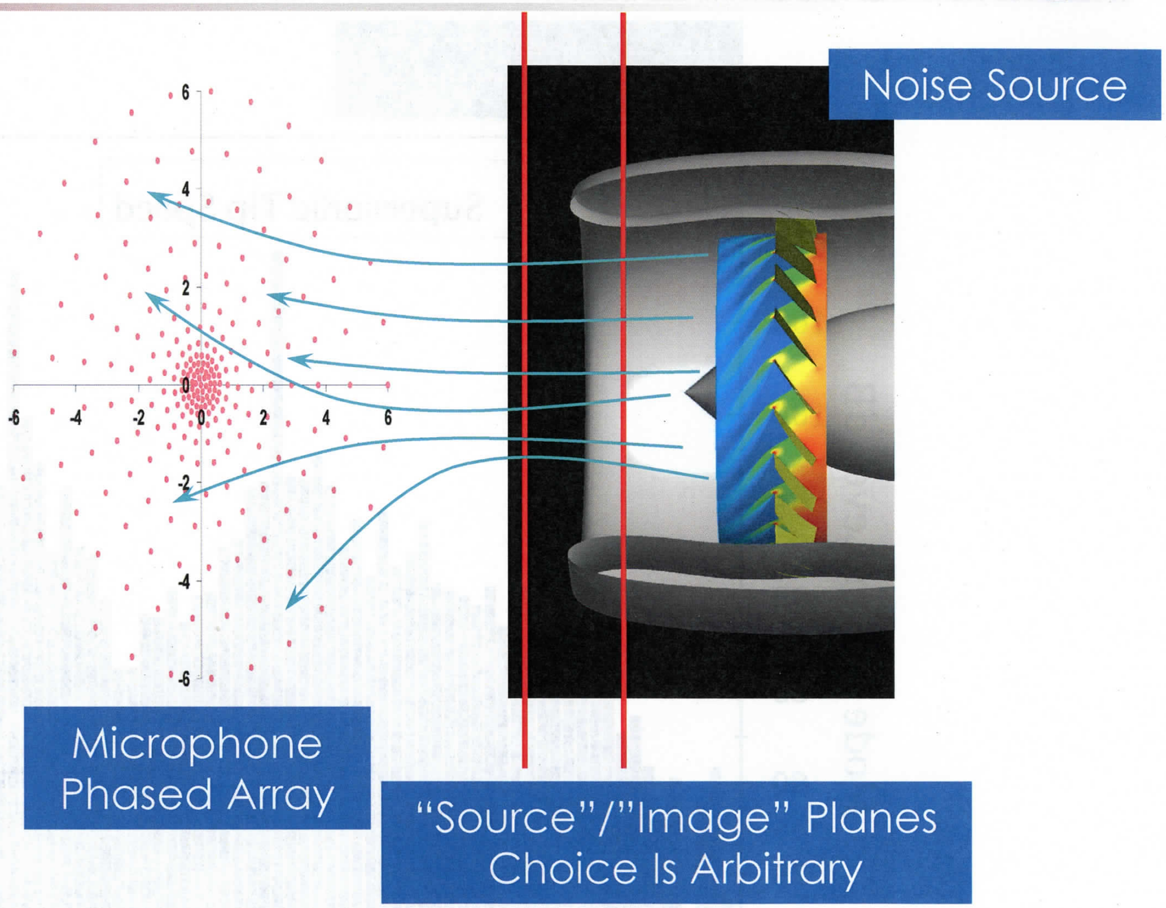
NASA Data – 2BPF Tone
SDT Fan (2000)



Measurement

Phased Array Technique

Phased array is a relatively modern tool for source identification and localization. It consists of a microphone array that is aimed at a source (or source region) so that each individual microphone can "see" the source and acquire acoustic data from it. The acquired data is then processed using a specialized technique called beamforming to create an "image" of the source distribution on an arbitrarily chosen plane. The image provides information about the apparent spatial and spectral distributions of the sound field.



$\mathbf{C} = \left\langle p' p'^{*} \right\rangle$: Cross-Spectrum Matrix

$\mathbf{g}_i$: Steeting Vector

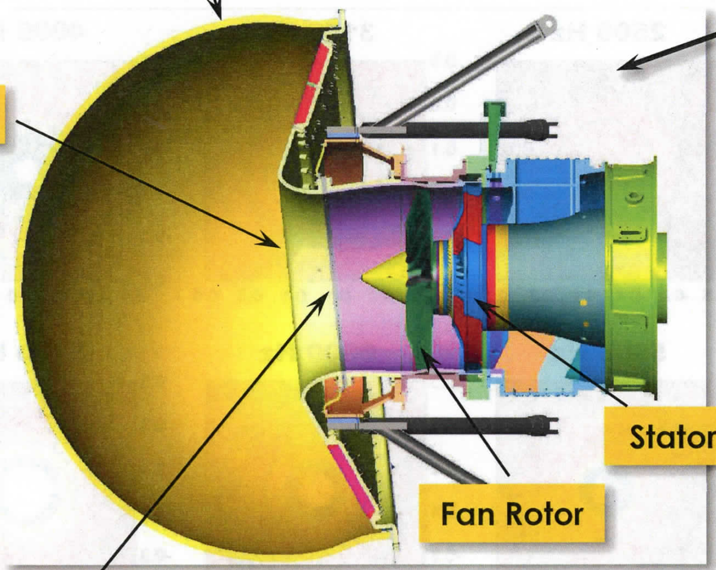
$\mathbf{A}$: Souce Power Spectrum at the Image Plane

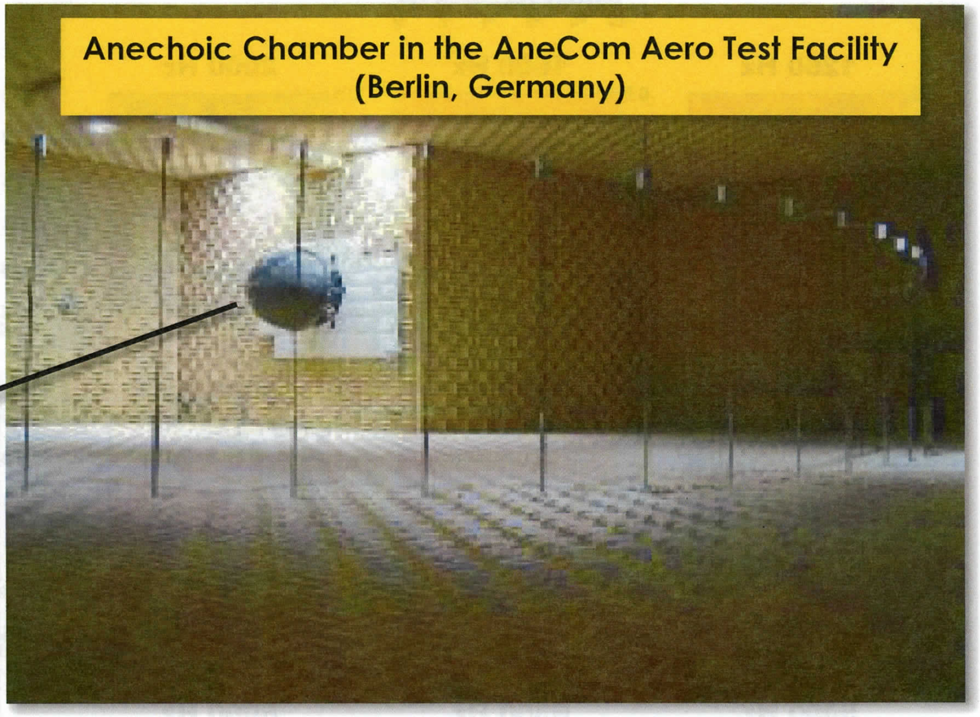
$$\mathbf{A}_i = \frac{\mathbf{g}_i^{*} \mathbf{C} \mathbf{g}_i}{\left(\mathbf{g}_i \mathbf{g}_i^{*}\right)^2}$$

Measurement

Phased Array Technique (Cont'd)

In this example the phased array is the microphone ring inside the inlet.

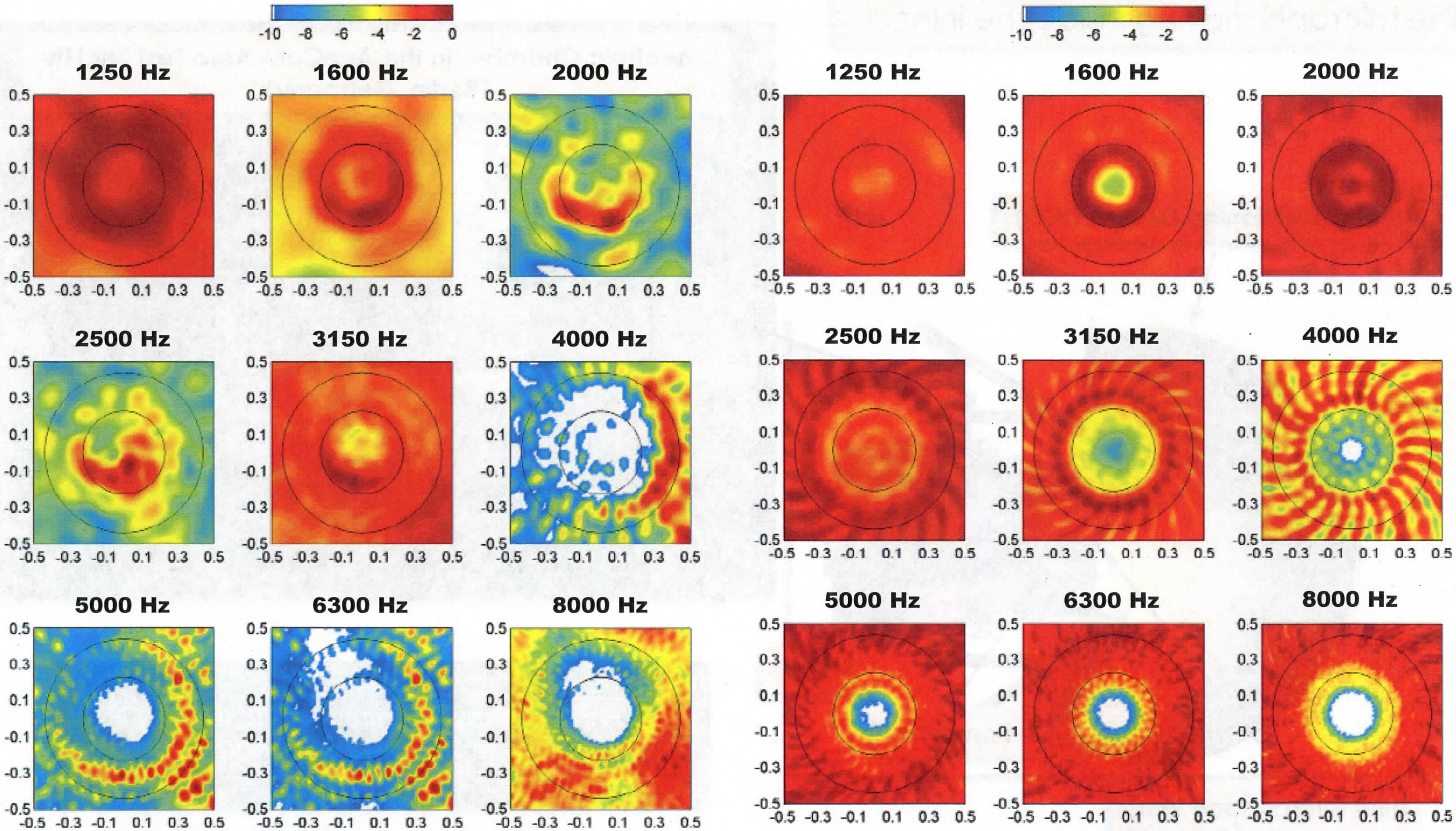




<u>Reference</u>
Using Phased Array Beamforming to Identify Broadband Noise Sources in a Turbofan Engine
Pieter Sijtsma, NLR, (Bilbao 2008)

Phased Array Technique (Cont'd)

Beamforming Results for Stationary Focus and Rotating Focus



Stationary Focus (Stator LE)

Rotating Focus (Rotor LE)

Measure

Modeling & Prediction

Modeling Challenges

- The fundamental challenge of aeroacoustic modeling is the large difference between the aerodynamic and acoustic scales;

Aerodynamic: $p \,/\, p_{amb} \sim O(1)$

Acoustic : $p' \,/\, p_{amb} \sim O(10^{-3} - 10^{-6})$

- This difference necessitates the development of specialized modeling techniques to adequately resolve the acoustic perturbations. This is most often done by separating the two scales through linearization of the equations of motion.

Modeling Challenges (Cont'd)

- In linearized methods, the mean flow and some aspects of the source description (e.g., amplitude, length/time scales) are specified, measured, or computed *a priori* and are introduced as boundary conditions or source terms in the equations governing the acoustics. Therefore, the accuracy of the input is paramount in view of the large ratio of aerodynamic and acoustic scales.

- A further simplification often employed in inlet noise modeling is to separate the generation and propagation/radiation aspects of the problem.

Linearized Inviscid Flow Equations

Depending on the application and assumptions made, some simplified version of the general set of perturbation equations listed below is used to model generation and propagation of sound in the inlet.

$$\frac{\partial \rho'}{\partial t} + \nabla \cdot \left(\rho_0 \mathbf{u}' + \rho' \mathbf{V}_0 \right) = \rho_0 q$$

$$\rho_0 \left(\frac{\partial \mathbf{u}'}{\partial t} + \mathbf{V}_0 \cdot \nabla \mathbf{u}' + \mathbf{u}' \cdot \nabla \mathbf{V}_0 \right) + \rho' \mathbf{V}_0 \cdot \nabla \mathbf{V}_0 + \nabla p' = f$$

$$\frac{\partial s'}{\partial t} + \mathbf{V}_0 \cdot \nabla s' + \mathbf{u}' \cdot \nabla S_0 = 0$$

$$c_0^2 \left(\frac{\partial \rho'}{\partial t} + \mathbf{V}_0 \cdot \nabla \rho' + \mathbf{u}' \cdot \nabla \rho_0 \right) - \left(\frac{\partial p'}{\partial t} + \mathbf{V}_0 \cdot \nabla p' + \mathbf{u}' \cdot \nabla p_0 \right) + c'^2 \mathbf{V}_0 \cdot \nabla \rho_0 = 0$$

Inviscid Mean Flow Eqs.

$$\nabla \cdot \left(\rho_0 \mathbf{V}_0 \right) = 0$$

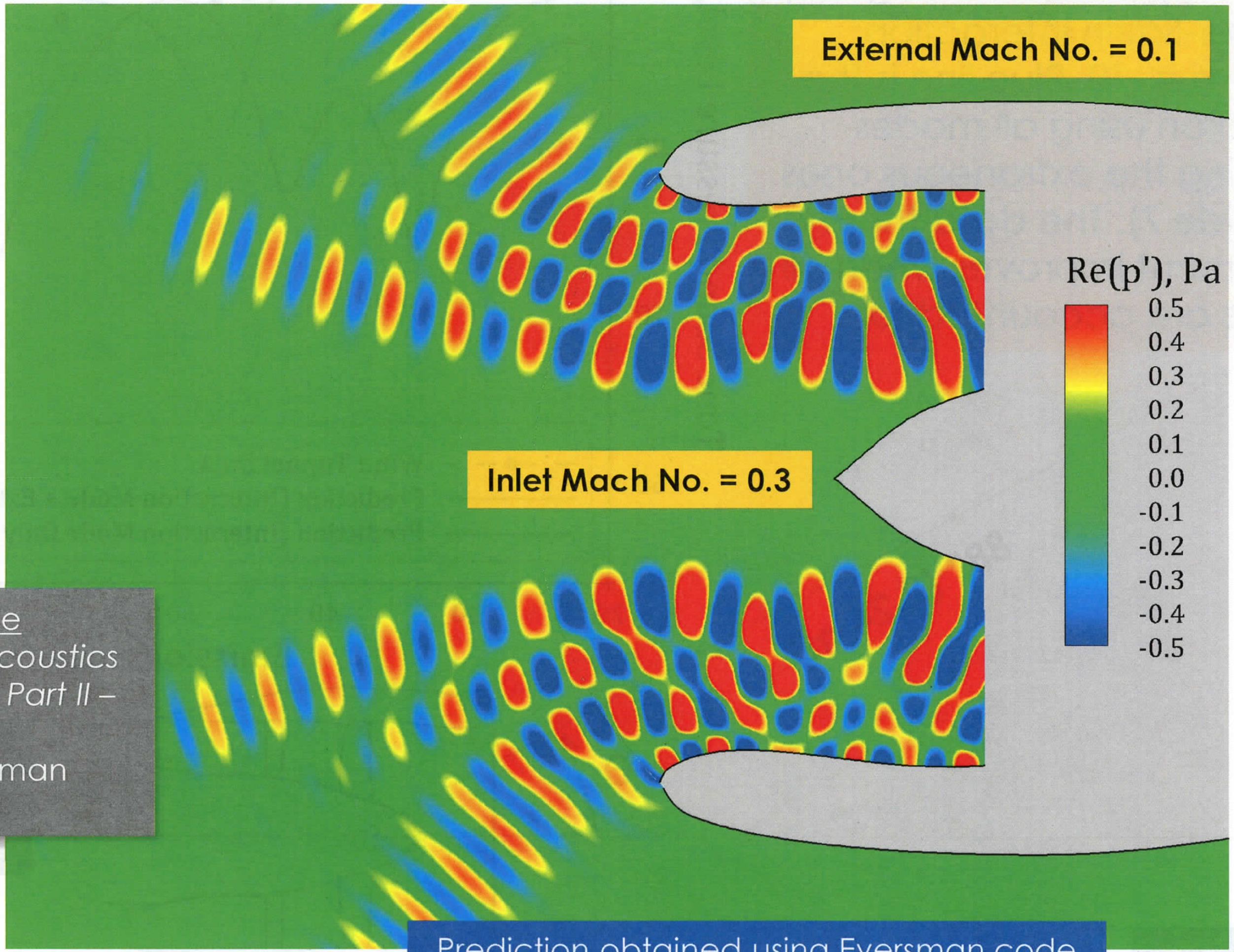
$$\rho_0 \mathbf{V}_0 \cdot \nabla \mathbf{V}_0 + \nabla p_0 = 0$$

$$\mathbf{V}_0 \cdot \nabla S_0 = 0$$

$$c_0^2 \mathbf{V}_0 \cdot \nabla \rho_0 - \mathbf{V}_0 \cdot \nabla p_0 = 0$$

Propagation/Radiation Prediction

Example: Inlet Radiation Calculation for SDT Fan at Approach Condition
Source input specified from Rotating Rake measurements upstream of the fan face. Only Tyler Sofrin-Mode *m* = -10 is included in the calculation.



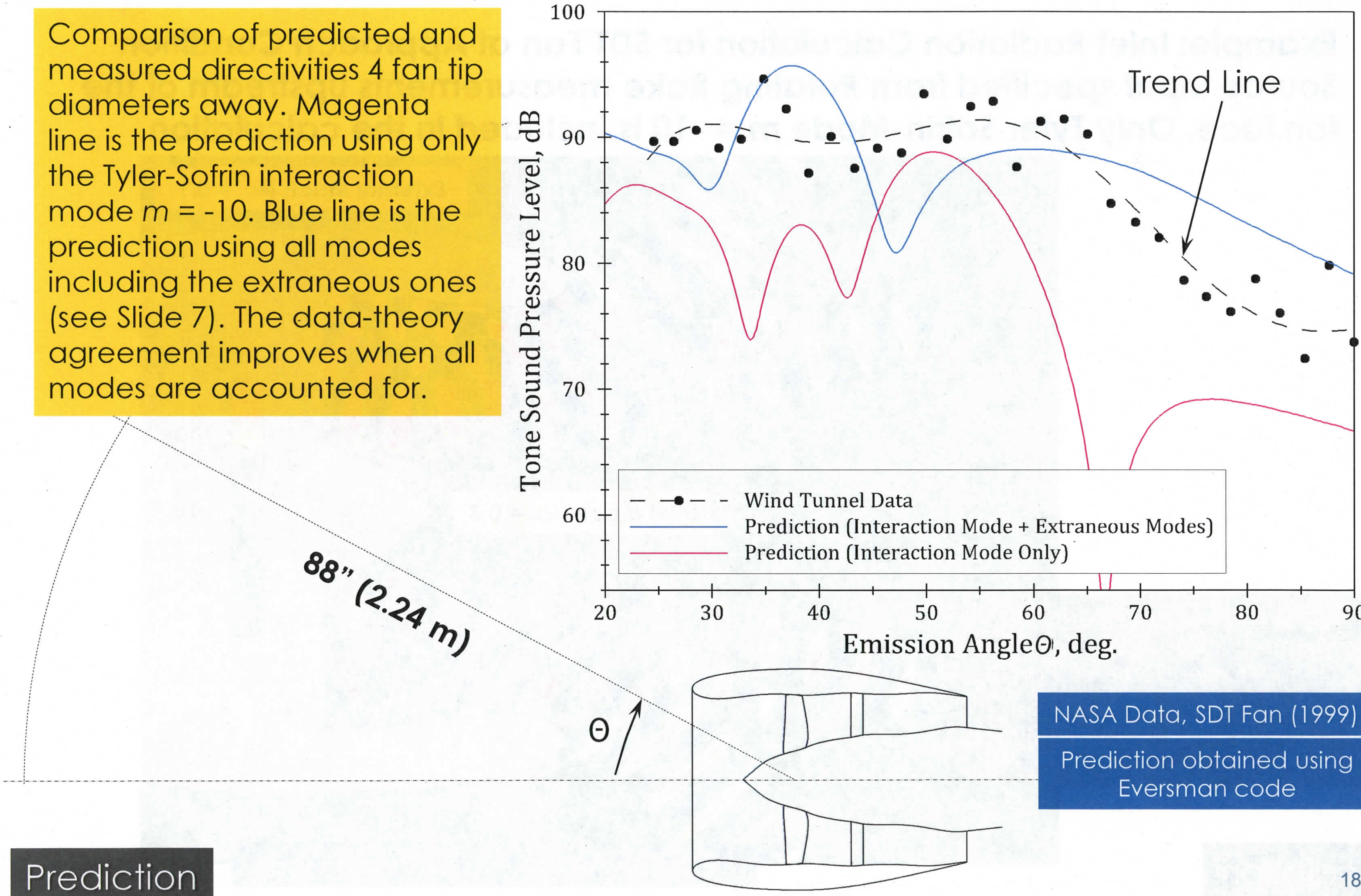
Prediction obtained using Eversman code

Reference for Eversman Code
Finite Element Modeling of Acoustics Using Higher Order Elements: Part II – Turbofan Acoustic Radiation
Eivind Listerud & Walter Eversman
(2004)

Prediction

Propagation/Radiation Prediction (Cont'd)

Comparison of predicted and measured directivities 4 fan tip diameters away. Magenta line is the prediction using only the Tyler-Sofrin interaction mode m = -10. Blue line is the prediction using all modes including the extraneous ones (see Slide 7). The data-theory agreement improves when all modes are accounted for.



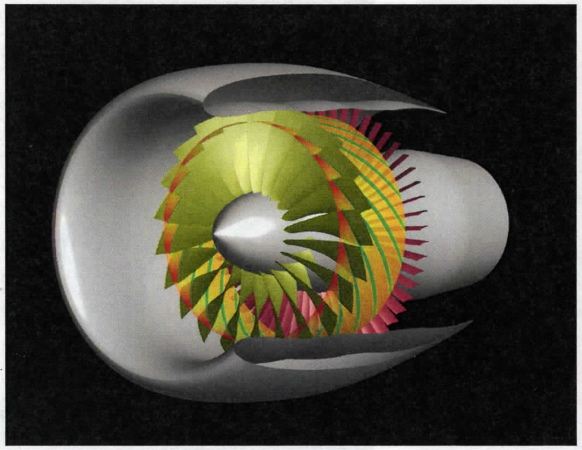
NASA Data, SDT Fan (1999)

Prediction obtained using Eversman code

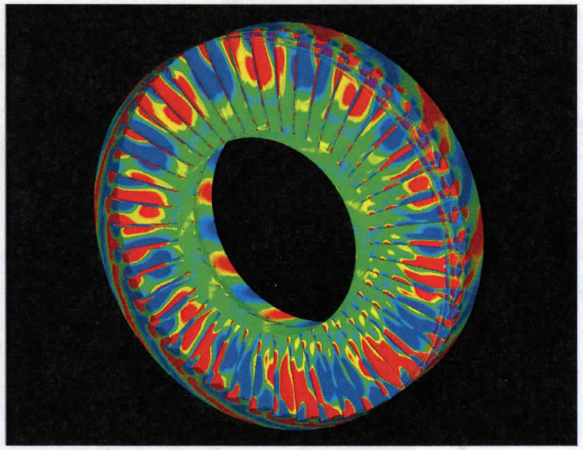
Prediction

Source Prediction: Rotor-stator Interaction

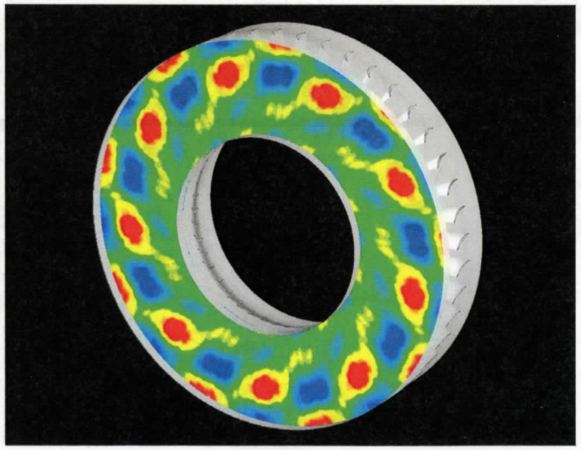
Using CFD the rotor blade wake field can be calculated and used as input in a linearized simulation of the stator response to the incident wakes. The upstream propagating acoustic pressure field can in turn be used as input for a transmission loss calculation through the rotor to compute the portion of the acoustic energy that makes is through the rotor. This calculation can also be done using a linearized Euler approach. Finally, the resulting transmitted pressure field can be used as input for an inlet radiation calculation (of the type shown in the previous slide) to predict the farfield spectrum of rotor-stator.



RANS simulation of rotor wake field. SDT fan at approach tip speed condition.



Linearized Euler simulation of stator response to incident rotor wakes. Approach tip speed condition; 2BPF content of the unsteady pressure distribution on the stator is shown.

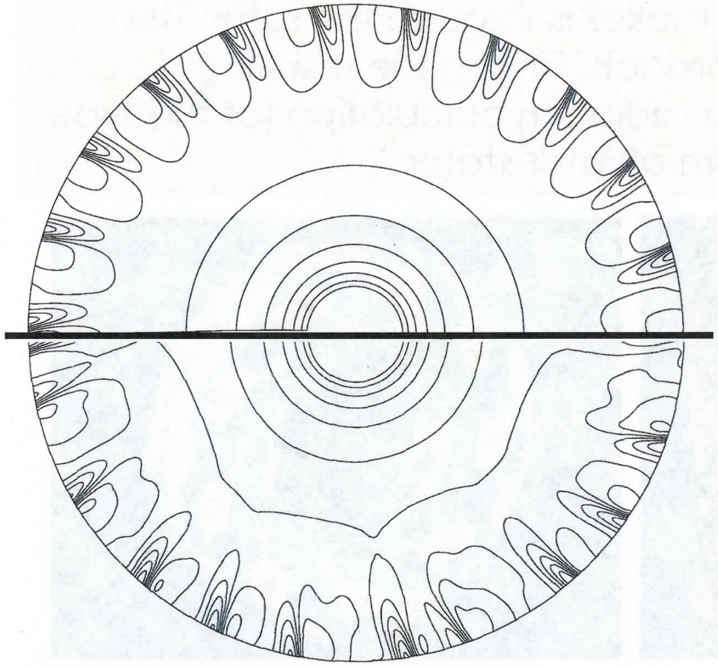


Linearized Euler simulation of stator response to incident rotor wakes. Approach tip speed condition; 2BPF acoustic pressure field propagating upstream away from the stator is shown.

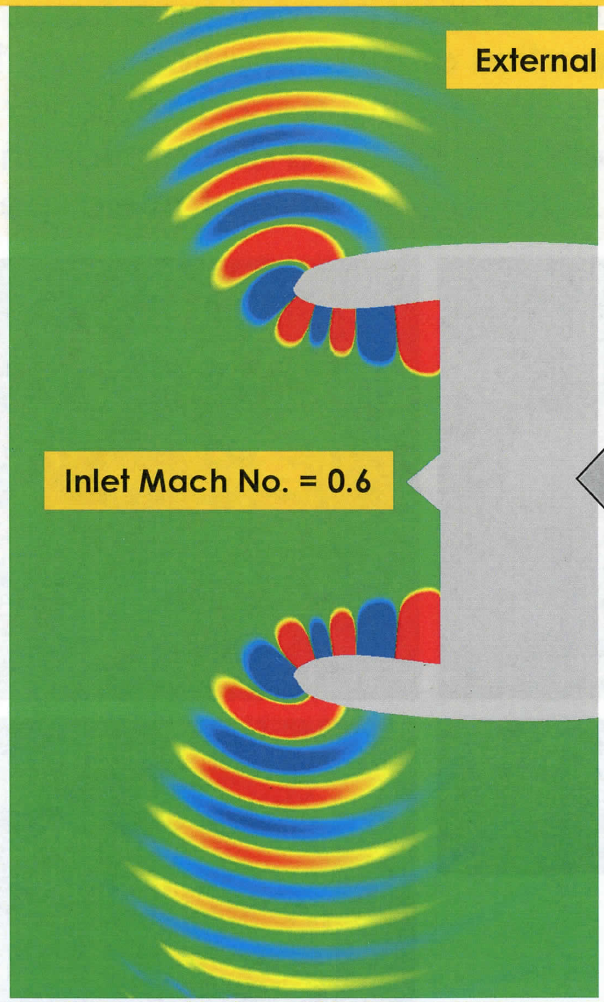
Prediction

Source Prediction: Multiple Pure Tones

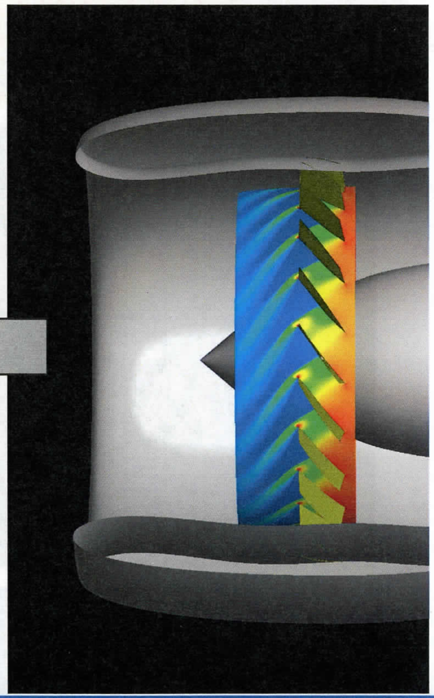
Using CFD the static pressure field of non-uniformly staggered fan blades can be calculated and used as input for an inlet radiation calculation to predict the farfield MPT spectrum.



An example of RANS-based simulation of fan flowfield due to blade-to-blade stagger variations (bottom half). For comparison the uniform stagger case is shown in the upper half. Static pressure distribution shown upstream of the fan.



Duct radiation prediction obtained using Eversman code.



SDT fan RANS simulation for transonic tip speed. Uniform stagger shown.

Mitigation

Mitigation Techniques

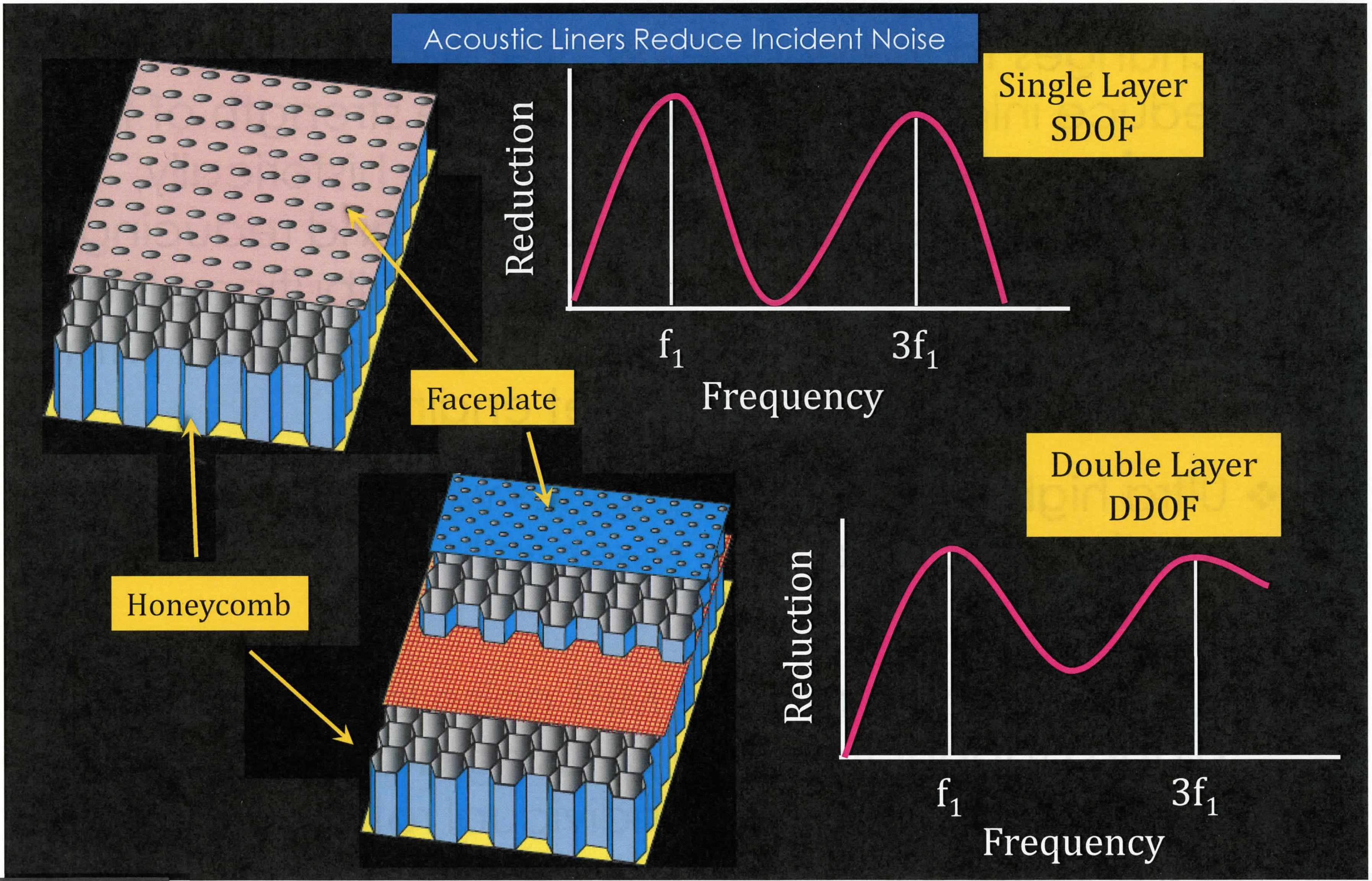
- The principal method for mitigating inlet noise is to use acoustic liners to absorb the sound before it leaves the inlet. The liners typically are designed to target specific frequency or a narrow range of frequencies.

- Although "bulk" liners can be constructed to absorb a much broader range of frequencies, they tend to be adversely affected by rain and dirt and lose their effectiveness quickly.

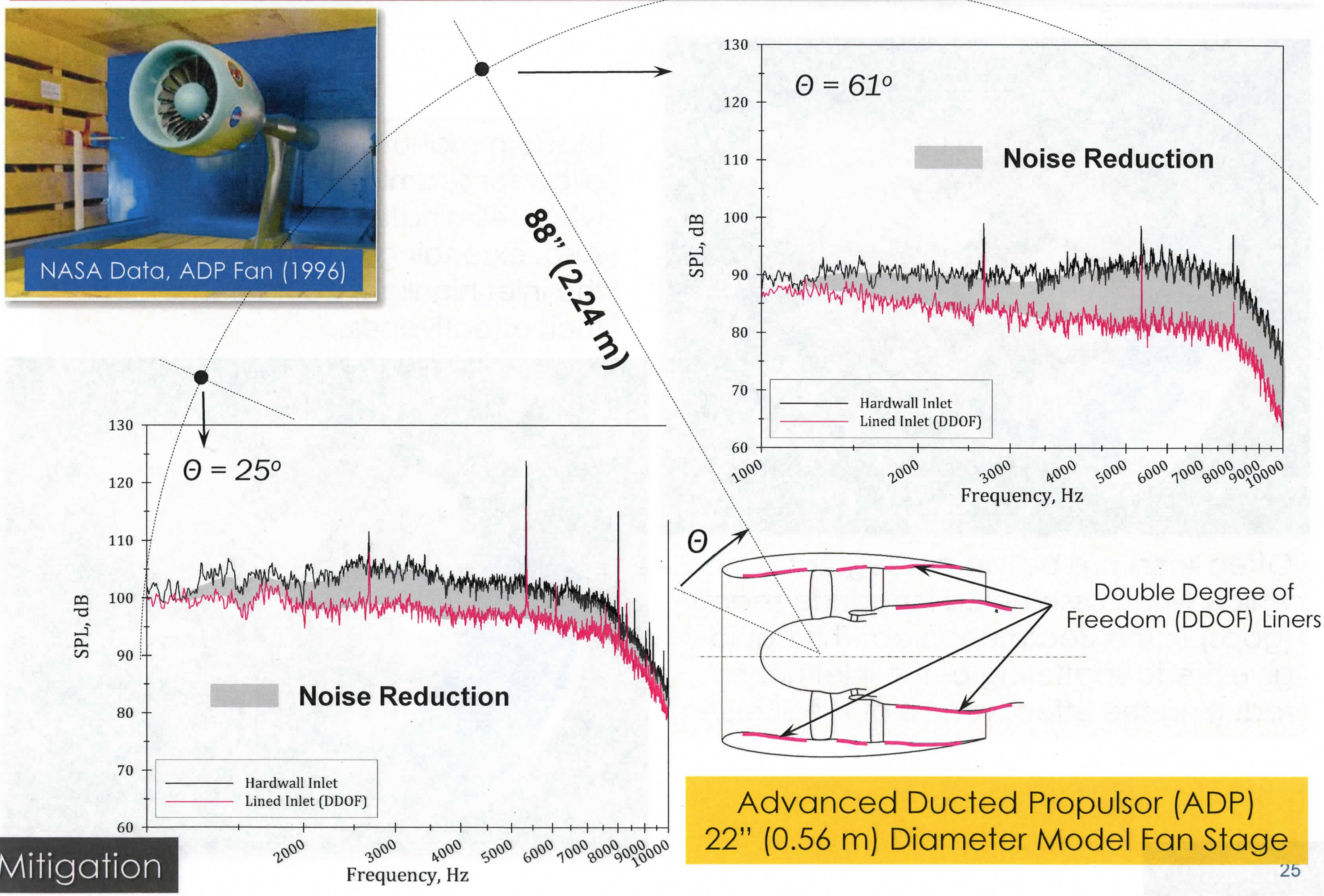
Mitigation Techniques

- Changes to the engine architecture can also reduce inlet noise by reducing the strength of the engine noise sources. For example, historically, increasing the engine bypass ratio and reducing fan tip speed has reduced the contribution of fan and jet noise sources significantly compared with the early generation turbojet engines.
- Ultra high bypass ratio engines with rotor subsonic relative Mach No. can essentially eliminate MPT noise.
- Another way to reduce MPT noise is to reduce blade stagger variation by using a blisk design rather than assembling individual rotor blades into a rotor disk.

Acoustic Liners



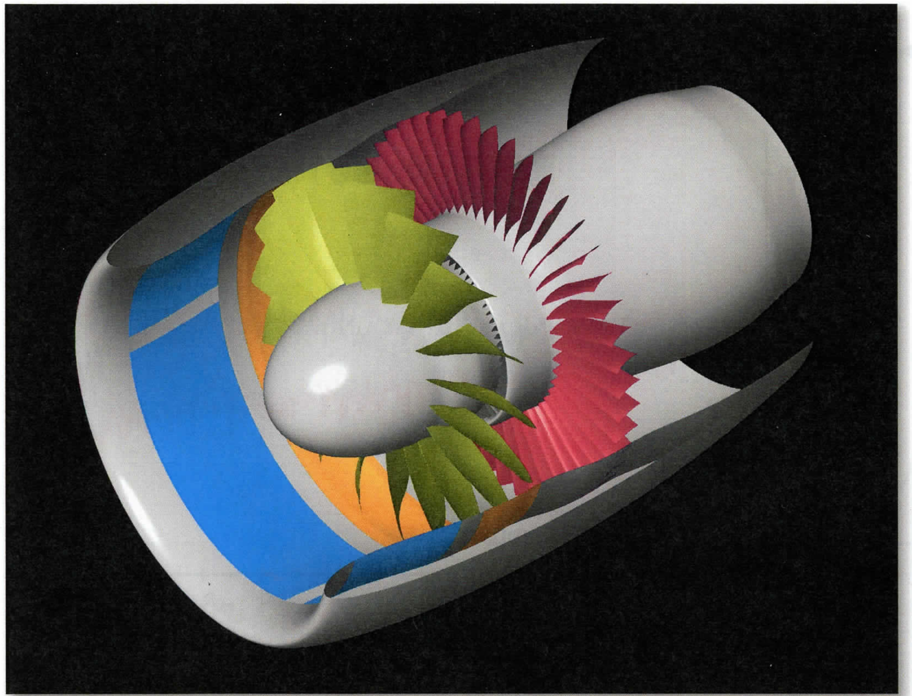
Example of Liner Effectiveness



Advanced Ducted Propulsor (ADP) 22" (0.56 m) Diameter Model Fan Stage

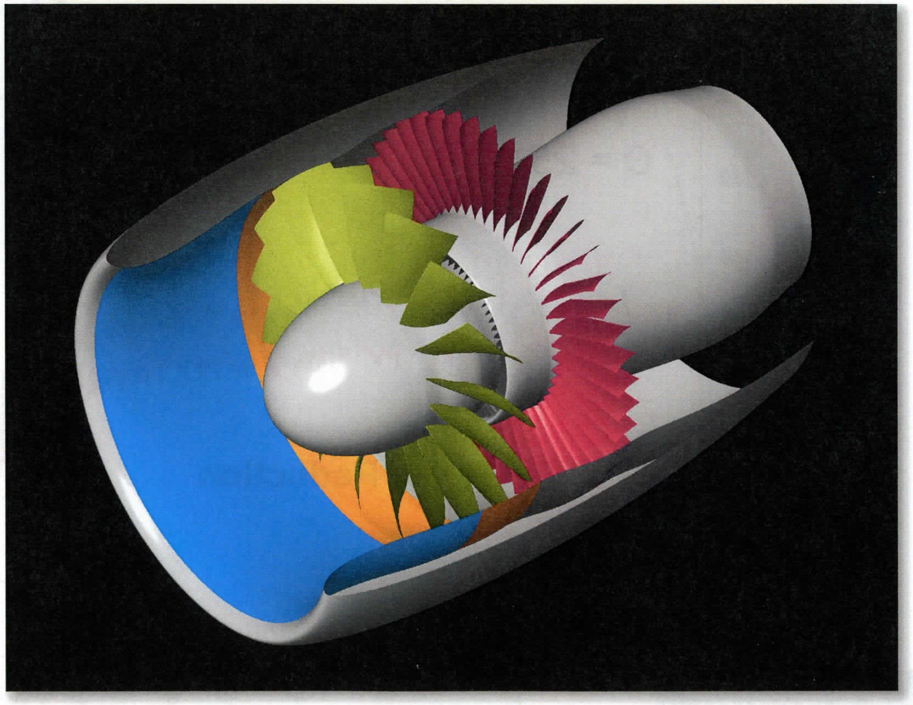
Mitigation

Improvements in Liner Design



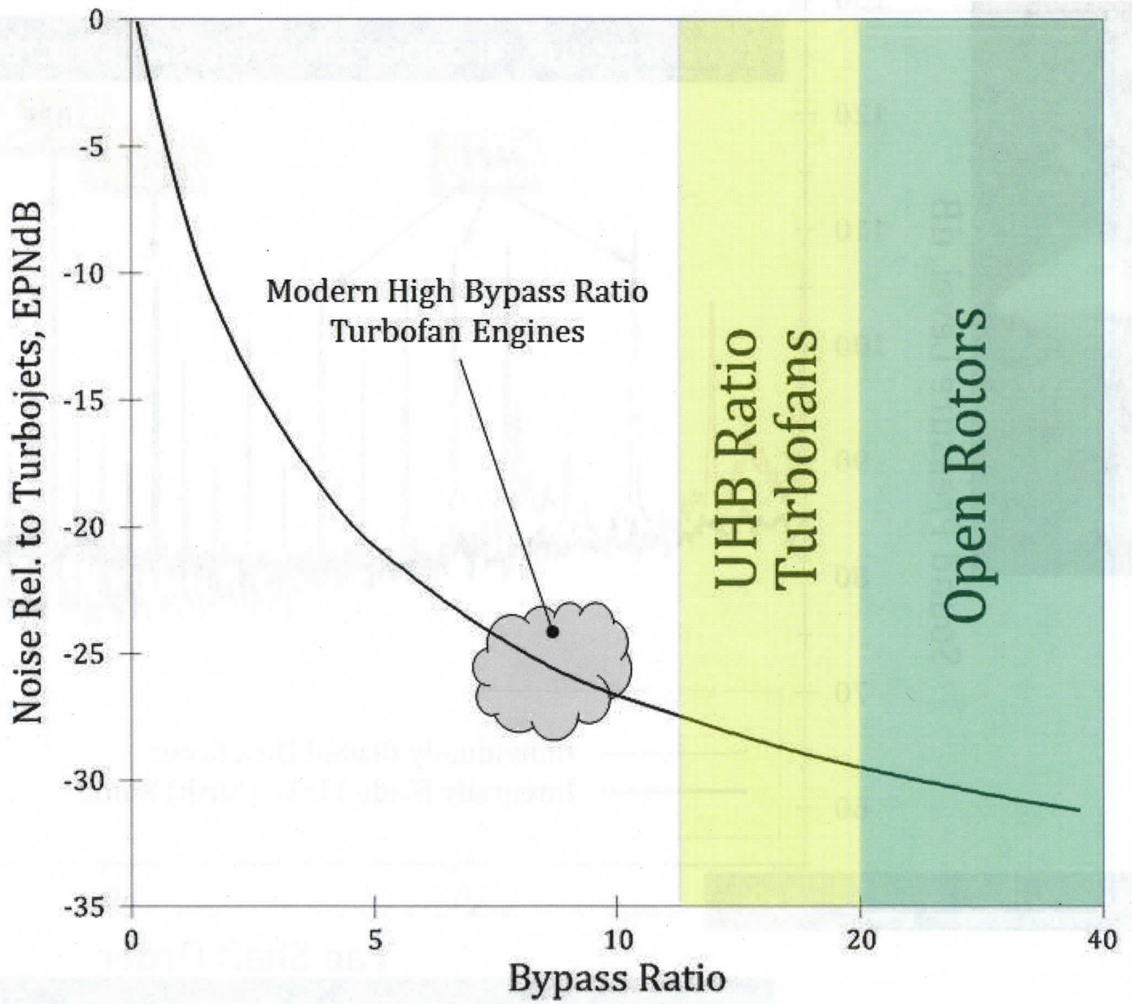
Often liners are built in arc segments which when assembled introduce seams (gaps) in the treatment area. This could give rise to scattering of the inlet noise reducing the effectiveness of the liners.

Modern manufacturing techniques allow for seamless liner construction which eliminates the scattering issue. Also, extending the liners closer to the inlet highlight could enhance their effectiveness.



Engine Design Changes

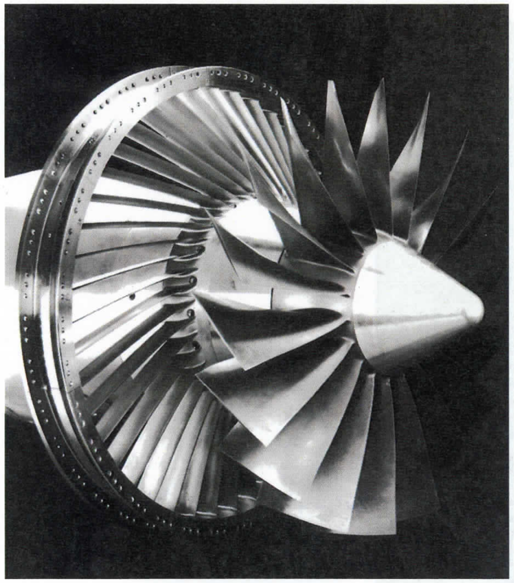
Increasing the bypass ratio is a powerful means of reducing the strength of engine noise sources and potentially even eliminating some source altogether. For example, strictly subsonic tip speed fans do not generate multiple pure tone (MPT) noise.



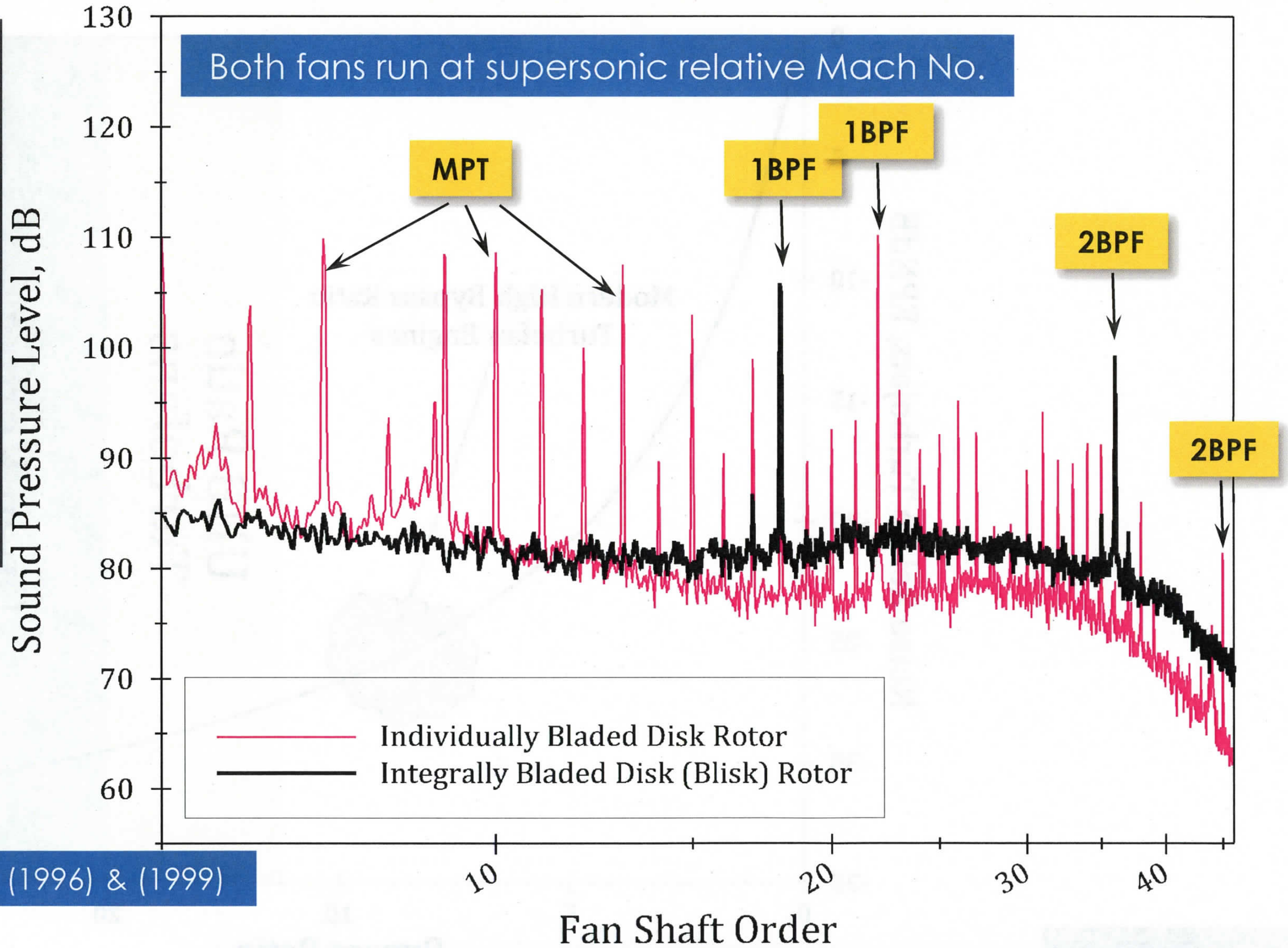
Mitigation

Influence of Blisk on MPT Noise

As the figure below indicates, blisk rotors do not produce MPT noise since there is little if any stagger variations in such designs. Of course, blisk design is not practical for large diameter fans and tends to be limited to small engines.



Blisk Fan



NASA Data, (1996) & (1999)

Measured Noise Level 4 Fan Diameters Away at 60° from Inlet Axis

Summary

- Inlet noise can be measured and characterized directly using the Rotating Rake system and phase array techniques.

- For the most part, the generation and propagation/radiation of inlet noise can be modeled using linearized inviscid flow equations.

- The use of acoustic liners are the principal is the principal method for mitigating inlet noise. Reduction of fan tip speed is also an effective way of reducing inlet noise. For small diameter fans, blisk construction can reduce or eliminate a major source of inlet noise at supersonic relative Mach No., namely, MPT noise.

Questions?